An agent-based model to explore a pluralism of land regulation in rural Sahel: supplementary data

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1. CONCEPTUAL MODEL

i. Purpose

The purpose of the model is to support the exploration of a stakeholder-oriented pluralism of regulation regarding the use and management of Sahelian natural resources. The agent-based model simulates the diverse decision-making processes (i.e. the logics of action) of different land actors (users and regulators) when they interact for the access and the use of land and water in a Sahelian environmental context. The outputs of the model result from the simultaneous implementation of the diverse individual decision-making processes.

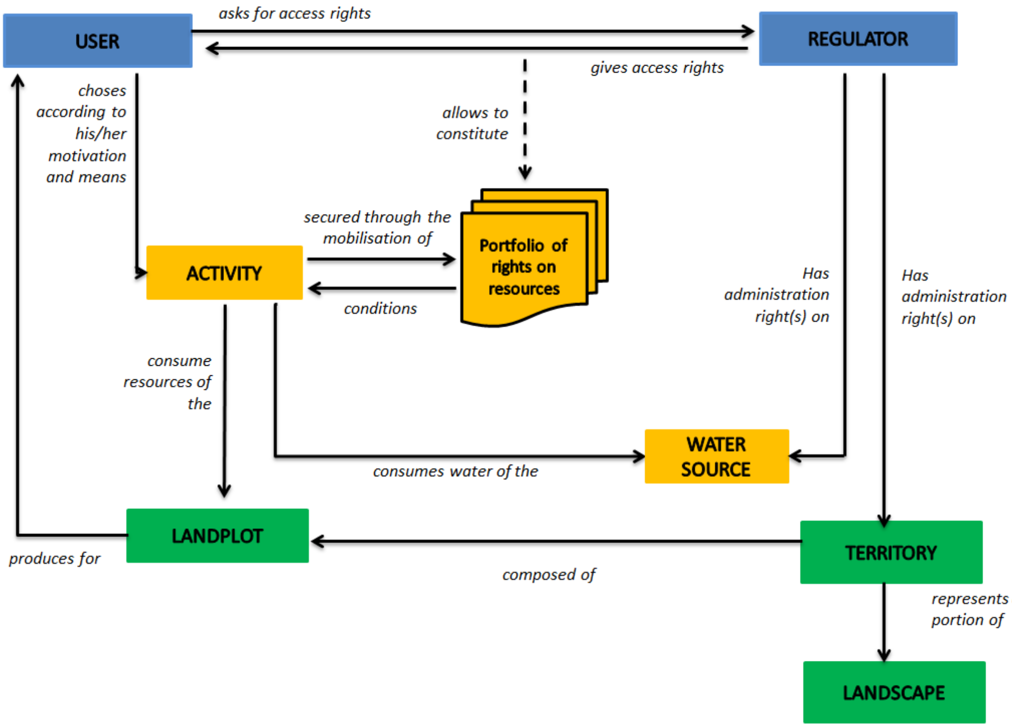


Figure 1: Conceptual model of the entities' interactions

LEGEND	INFORMATIC TRANSLATION
RESOURCES	Spatial Entities
AGENTS	Social Entities
	Passive Entities
	Collection (attribute of agents)

To help formalize these uncertain, flexible logics, we performed a direct conceptualisation of the stakeholders' points of view, respecting their perception of the different sources of regulation that can be used according to their own decisions. The model is therefore focused on actors' perceptions, which means it takes into account every land regulation sources that the actors recognize and use, regardless of whether or not these sources are legally recognized. This is in a way a stakeholder-oriented conceptualization framework.

In this regard, in much of the Sahel, land, natural resources and water official regulations have evolved with very little coordination, and often in different directions. But from the Sahelian actors' perceptions, these different resources are still closely embedded and it is the inseparable association of it that allows them to realize their activities and to produce the food they need. In order to condense the analysis of this complex reality and try to preserve the stakeholders' perceptions, water is considered in this study as one of the Sahelian natural resources. Even if the focus is made on land, the same reasoning applies to water sources and their regulators as the one developed below for land regulators and their territories. We consider in this study the term "land" as the gathering of all natural resources from which a user can request access[1].

ii. **Case study of Senegal, a Sahelian country**

The modelled conceptual framework result from a combination between a bibliographical review, and a field experience through two regional case studies in Senegal, a Sahelian country. The field experience was conducted in two parts:

- between April 2011 and June 2013 we conducted three hundred individual semi-structured interviews within two rural areas in Senegal (Ferlo sylvo-pastoral area and the developed part (mostly irrigated) of the river Senegal valley) considered representing national diversity in terms of issues, tensions and uses that can be made of the land. The two zones differ in their degree of integration of intensive farming, accompanied by a more pronounced appearance of official sources of land tenure regulation in the users' practices for access to land;
- in April 2014, a role-playing game was realized and experimented in these two rural areas to test the reality and conditions of the local mobilization and use of the different sources of land tenure regulation. Two participating workshops, each with 20 players (5 players per board) were set up in the villages of Sinthiou Bamambé in the Ferlo sylvo-pastoral area and Guia, in the the river Senegal valley.

a. The Sahelian environmental context

The Sahelian zone is characterized by extreme ecological and climatic spatial variability and uncertainty. The climate is dry and the rains and temperatures are unpredictable, as highlighted by extremely localized differences in their temporal and spatial distribution. The rainfall quantity varies strongly not only from one year to the next but also over the same year from a land plot to another. Consequently, the level of available resources (such as soil fertility, fodder, non-timber forest products (NTFP)…) vary widely according to the rainfall local context. This ecological variability is also geographical, given the topography and fertility of the soils. Overall, this leads to a very dispersed, heterogeneous and unpredictable distribution of environmental conditions over the years and within a given year.

b. Regulation of the Sahelian natural resources

[1] All in all, the land resource can cover the flora, the fauna, and the hydraulic systems as long as they are associated to a space of land (de Zeeuw, 1995).

Sahelian inhabitants, who have evolved for centuries in this setting of extreme variability and uncertainty, have forged territory management rules tailored to this uncertainty and scarcity of resources (Ellis et al. 1988, Mehta et al. 1999)..

First, with land rules and a social organization conducive to high mobility of people and activities (especially pastoral transhumance) (Behnke and Scoones 1992), it is possible to take advantage of the best of this variability by searching and exploiting the best environmental conditions where they are temporarily located. Natural resources not being available enough on the same land plot, it requires users to go fulfill their need of natural resources where they can find some. It is also possible to observe on the same land plot multiple different access rights (linked to multiple users).

Indeed, collective management is preferred over individual appropriation of these resources (Berkes et al. 1989, Ostrom 1990), which are too sparse to be appropriated by an individual. The complex rules that are implemented aim to allow a maximum of individuals to benefit from access to some of these resources. Local rules applied in the Sahel are temporally flexible and dynamic and thus favorable for multi-uses (Gallais 1977, Le Roy et al. 1996, Mwangi and Dohrn 2008). Some activities being periodic, seasonal, annual, it requires a frequent renewal of the access rights.

Choices of activity are linked to a flexible resource exploitation system, based on the integration of multiple activities (several types of farming combined with several types of breeding, harvesting etc. which may require water, and seasonal movements). The logic underlying this exploitation system is focused on a diversification of income sources rather than on the practice of a single intensive activity, which would be too subject to chance and uncertainty.

Choices of activity are also linked to the availability of the water resource. Some activities are indeed not feasible without water supply (for example any breeding activity which requiring the watering of the cattle). Moreover, rural activities are distributed in cropping season, the main representation of Sahelian cropping season temporality being the succession of rainy seasons (from June to October) and dry seasons (from October to June). During the rainy season, rain allows any cropping activity even if a more permanent access right to a water source (like a drilling, a well, a riverside, a hydro-agricultural canal…) is not obtained. Conversely, during the dry season, no rural activity is feasible without a water supply.

c. The bundle of rights approach

In order to describe the multiple forms of rights coexisting within the same area researchers have focused on a “bundles of rights” approach (Le Roy 1996, Mehta et al. 1999, Ribot and Peluso 2003,…), allowing identification of “operational rights” (dealing with land uses) and “administration rights” (dealing with the management of these operational rights, their distribution, conflict settlement, sanctions, etc.).

The “bundles of rights” concept illustrates that there is not one right on the land resources, but numerous rights (to use, administer, transfer, etc.), on various resources (land, trees, forest products, water etc.), and that these rights may be claimed by various users (individual or collective) and under the control of different authorities. A bundle of rights can include: access rights; rights to use; rights to earn income from the use; rights to invest in the use; rights to delegate land use temporarily or without specific terms, in marketable (rent, sharecropping) or non-marketable terms (loan); the right to pledge; and the right to definitively alienate, through a marketable transfer (sale) or donation.

These land rights can be available all year, or only over a certain period (for example a right to use only during the dry or the rainy season) and for a certain duration, from the cropping season up to several years (for example, a user can benefit from a right to use a land only for rainy season during all his life).

Access rights can be free, or linked to a certain monetary or non-monetary cost (gifts, labor force, sharecropping, loan, rent etc.).

The nature of the land right, what it allows, its cost, its duration, and a set of other criteria help constituting a specific perception of land tenure security for each Sahelian user, which conditions his choice of rural activity in relation with the act of investment he can consider. Indeed, the perception of land tenure security can be affected by the nature (and the need of investment) of the rural activity performed (Bruce and Migot-Adholla 1994). For example, an oral periodic right to use a land only during the rainy seasons can be considered safe enough to realize extensive cropping (millet, sorghum, maize, fonio…), but not safe enough to start more intensive cropping (groundnut, fruit trees, market gardening…). Land tenure security is therefore in this approach considered as a feeling, resulting from a dynamic process which changes and adapts itself to the conditions of a given context (Bruce and Migot-Adholla 1994, Le Roy 1999, Cotula 2012).

Besides, even if the focus is made, for the clarity of the analysis, on the consideration of two main types of distinct land actors (users and regulators), the boundaries between users and regulators can in reality be very fuzzy. When Sahelian users benefit for example from a part of the bundle of rights that allow them to delegate their land access right, they become themselves regulators, and can decide according to their own logic of action to share their land with other users, through marketable (rent, sharecropping) or non-marketable terms (loan).

This last statement leads to the question of the spatial and social scale of exploration of the stakeholder-oriented pluralism of regulation. Whether we consider the regulation or the use of land resources, each “collective scale”: a family, a village, a lineage, a local community, an ethnic group, etc. can include intra/inter forms of land regulation pluralism, which express itself to the spatial scales of a land plot, a farm, a territory village, a rural community, a region, a country…

d. A stakeholder-oriented pluralism of land regulation sources

As the land tenure policies set up by states do not recognize the local regulation sources described above, they have used approaches to land tenure and ownership that are too different to the local context for it to be possible to remove them (Mwangi and Dohrn 2008). The management of land resources is therefore built on several overlapping land regulation systems where numerous regulators intervene.

The Senegalese decentralization land policy officially provides a territory management mandate to local communities, who deliver land allocations, equivalent to authorisations of use of the land (users are usufructers of the land they farm). The central State continues to take part in this management, for example by allotting large portions of land through land title (private ownership) often to State members or big investors. Moreover, even if local communities are the official designated territorial management regulators, the traditional system, as described above, is commonly respected, and customary headmen can remain the reference regulators for anything concerning land and natural resources (drawing up of rules, land allotments, regulation conflicts).

This stakeholder-oriented conceptual framework led us to considering the various systems of rules as simple 'potential' sources of regulation. The term 'source' carries the idea that users make partial use of a set of rules and regulatory authorities with no systemic approach. It is not because a user decides at time t to use a particular authority or a particular regulation that he will necessarily adopt the entire functioning and logic of the system with which it is associated. Local stakeholders construct their own 'operation puzzle' by taking pieces for this from the different systems available to them. The puzzle changes as time goes by according to experience and local social interactions that modify the legitimacy of one regulation system or another, or rather of such and such a way of drawing a rule from a regulation system.

e. Interactions processes for the management and use of land access rights

Each regulator of these different land regulation systems has administration rights on a territory, representing a portion of the global landscape. Different regulators can have similar, complementary or overlapping administration rights on the same territories. During his exercise of administration, a regulator has his own perception of the ways he wants to implement the rules and laws on his land territory, and acts therefore according to its own logic, which is not necessarily compatible with that of other regulators. The focus for allocating resource access rights can for example be made on users' capital, favoring requests of the users with the highest capital or the most intensive activities. But it can also be made on users themselves, by adapting access authorizations to the assurance that all the users of the regulator territory have resource access rights. The focus for allocating resource access rights can also be made on resources environmental state or on customary principles (e.g. primacy to the initial establishment, or transmission to the first son) etc.

Sahelian users also apply their own logics of action, and the various present or past laws are interpreted and used—or not used—according to their perceptions. Users seems to mobilise this pluralism of land regulation at least partially by following an imitation logic, adapting themselves to the prevalent land regulation source (whether it is formal or informal) active in the rural zone where is situated the resources for which they require the access. A user who wants to access a resource will base his decision on the ways the other users that already exploit the spaces which interest him have obtained their own access rights. Another component of a user land tenure security would therefore be the recognition by the other users, because this recognition assures him a non-contesting of his resource access right(s). This prevalence of a land regulation source could be defined as the source of regulation which is the most mobilized by the users of the area already exploiting the concerned natural resource. The prevalence is therefore associated with the nature of the rural activity users want to realize (because this choice of activity defines the need of natural resource: soil fertility if a user wants to farm, fodder if it is a breeder, NTFP if he wants to harvest etc.).

In the same rural zone, several sources of land regulation can overlap according to the activities (and thus the different concerned resources). Some farmers of the area can for example mobilize an official instance such as a local community (or the State) in order to obtain a land allocation (or a land title) for their land while at the same place and time, pastures for the breeders are still managed by oral agreements delivered by customary headmen, with no recognition from the senegalese land law. Following these conditions, a new land regulation (like a new land use policy for example) will be really effective only in the rural zones where it becomes a way of accessing natural resources settled in the practices of the users of the concerned zone.

The nature of the new land regulations introduced until now by land use policies (land title, land allocation, lease…) do not seem to have a value for Sahelian users, they chose to mobilise the new regulation in a strategic way, because it seems to constitute their better land tenure security in the new land insecurity contexts where their already existing practises are not anymore enough. These new sources of land regulation do not initially result from actors practices. Users therefore consider these changes with a certain distance, mobilizing them only in the rural zones where their peers have already legitimized them in their practices of land access. This legitimization seems more to prevent users from the possible effects of these new imposed regulations than to reassure rights susceptible to be locally questioned. This could explains why in the rural contexts where official land regulation sources have not much influence, traditional land regulations remain a sufficient level of safety for users to invest in their rural activities on the only basis of these "customary" informal land rights.

f. Adoption of a land regulation change within this stakeholder-oriented pluralism of land regulation sources

All in all, the evolution of the land tenure situation in rural areas in the Sahel thus shows that these policies have finally accentuated the existing complexity (Bruce and Migot-Adholla 1994, Platteau 1996, Mehta and Leach 1999, Cotula 2012). Indeed, rather than abandoning their practices, local populations have added the land tenure policies set up successively to their pre-existing sources of regulation. It does cause a certain uncertainty that is difficult to grasp (Metah et al. 1999, Mwangi et Dohrn 2008): different stakeholders make therefore claim rights to the same land by referring to different regulatory sources.

The dynamic and diversity of expression of this stakeholder-oriented pluralism of regulation is linked to the concept of perception thresholds, above which changes are observed in users' practices of mobilisation of land regulation sources, but below which no matter the nature of the introduced change (for example, a new land use policy), it does not seem to be perceived, or in any case considered by Sahelian users.

Changes in land regulation can be introduced through a diversity of **intensities** (as the proportion of users mobilizing this new land regulation source on a same area) and **configurations** (as the spatial distribution of the users mobilizing the new land regulation source). This leads to a diversity of landscape composition evolutions at a general scale, according to the introduced changes. For example, a new development project can bring changes in land regulation on one or several contigous areas (the project works with all the users of a village, of a local community, of a hydro-agricultural area…). A new land use policy will however concern all the users of the country, oftenly on a volontary basis (users have to launch the process of converting and formalizing their land rights). This approach have generally led to a weak foothold of the state in all the Sahelian countries who had initiate it. Another example is the one of a (foreign) land investment project, which concerns a few users (mainly only the investor(s)) but can have a large impact on the general landscape composition, according to the number of hectares concerned by the investment project.

According to the intensity and the configuration of the introduced change - coupled with a diversity of criteria such as the pre-existing perceptions of land tenure security that users of the area(s) concerned by the land regulation change have or not - the perception thresholds (and the mobilization of the new land regulation in consequence) will vary.

2. MODELLING THE SYSTEM WITH THE HELP OF THE CORMAS PLATEFORM

The modelled conceptual framework being a direct conceptualization of the stakeholders' points of view on this pluralism of land regulation sources, we chose to implement it (in order to explore it) within an agent-based model (http://cormas.cirad.fr/). Indeed, whenever it makes sense to take a range of actors having different characteristics into account, and to finely represent their interactions between one another and with their environment, the multi-agent modelling is an effective solution for effectively reporting this complexity (Bousquet, Barreteau et al., 1996; ComMod, 2005). Cormas – the platform used for the model construction – was specially developed by CIRAD for simulating natural resource management and is oriented towards the representation of interactions between stakeholders on natural renewable resource use. It allows to model distinct individual behaviors (agents) according to a diversity of logics (e.g. the various perceptions on pre-existing and/or new land regulation sources), which bring the agents to opt for different practices according to the context of the proposed simulation.

i. General overview of the agent-based model

The agent-based model allows the expression of a plurality of decision-making processes for the different social entities of the model:

- For the regulators, who manage water sources and land territories in which they allocate land or water access rights according to different logics of action;
- Fort the users, who choose activities requiring a need of water and land for which they interact with different regulation sources in order to obtain access rights. According to the response of regulators, users will finally realize activities and consume the resources of the land plots and the water of the water sources for which access rights have been obtained.

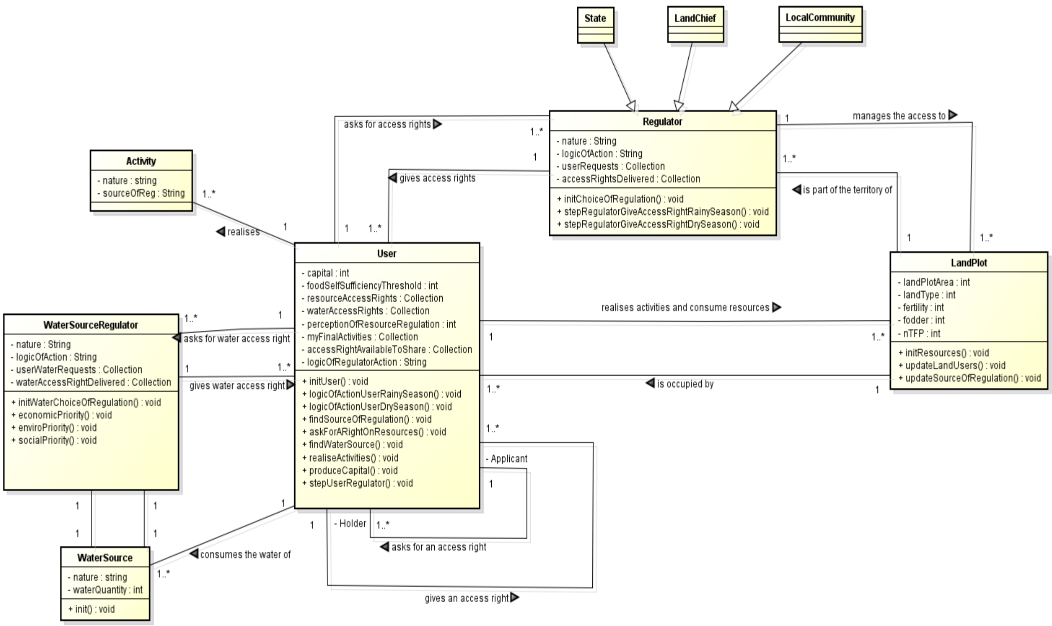


Figure 2: UML class diagram of the agent-based model

ii. Entities of the agent-based model

a. Spatial entities

The environment of the model represents a typical Sahelian territory composed of spatial entities knowns as land plots, which can be of different types: the lowlands, the intermediary sandy areas and the degraded lands (define through the attribute "LandType"). Each land plot containing a set of attributes on natural resources: fertility, fodder, and non-timber forest products (NTFP). The initial quantity of resource is the same of each type of resource on a land plot, but differs from one land plot to another according to the nature of the land type (lowlands being the most fertile areas, we find more important quantity of resources there).

This quantity is known through the multiplication of the size of the land plot (known through the land plot attribute: landPlotArea) with the value, according to the land type of the land plot, of the attributes: "lowlandSoilPerHaInit", "degradedSoilPerHaInit" and "sandySoilperHaInit". Indeed, each land plot has an attribute defining the area of the land plot. Three choices of value exist for this attribute, linked to three possible scales of land plot: 1 hectare, 50 hectares, or 1000 hectares. The quantity of each natural resource on each land plot is then updated after each rural activity which consume it (for example if the rural activity is breeding, it will consume the fodder resource) and at the beginning of each rainy season where natural resources are partially or totally replenished.

From an environmental point of view, the fertility of a land plot is considered "high" if the value of its attribute "fertility" is higher than one third of the initial fertility quantity. The value is similarly considered "low" if the value of its attribute "fertility" is lower than one third of the initial fertility quantity.

Each land plot has an attribute "localCommunity", an attribute "landChiefTerritory" and an attribute "Stateplot" that link the land plot respectively to a local community agent, a land chief agent and the state agent who are in charge of managing it. The land plots also have a set of attributes regarding the evolution of their availability of hectares for the different sources of land regulation: "availableHaLandChief", "availableHaLocalCommunity", "availableHaState". These attributes are by default equal to the value of the attribute landplotArea, and their values evolve according to the land activity of the different regulators who manage the landplot. For example, if a land plot area is equal to 50 hectares, and a user receives a right to use on this land plot for 10 hectares from a landChief regulator, the attribute "availableHaLandChief" will take the value 50-10 = 40 hectares.

Each land plot also possesses an attribute "landPlotUsers" which informs the users of who have resource access rights on the land plot, and especially from which regulator(s) the different user agents obtained those access rights. The attributes "Land Chief Regulation", "Local Community Regulation", "State Regulation" and "Other User Regulation" of each land plot then inform the modeler (and the users) of the general prevalent land regulation source at the scale of the land plot (by adding the number of access right delivered by each sources of regulation on the land plot).

At last, each land plot possesses a set of attributes: "Land Chief update", "Local Community update", "State update" and "Other User update". These "update" attributes are by default equal to zero, and it is by modifying the value of these attributes that the modeler can introduce changes in the sources of land regulation during the simulation. The modification of these values symbolize new (fictive) user agents that would access the resources of the land plot through this source of land regulation (the state if the modeler modify the state update attribute, the local community if he modify the local community update attribute etc.). These "update" attributes are part of the calculation of the prevalent land regulation source. Indeed, to define the number of users mobilizing a land regulation source at the scale of the land plot, the agent-based model adds the result from the collection "LandPlotUsers" to the value of this "update" attribute. For example, if the result of the consultation of the collection "landPlotUsers" shows that 10 user agents are exploiting the resources of the land plot through land Chief access rights, and that the value of the attribute "landChiefupdate" is 20, the total number of users mobilizing the land chief regulation to access resources will be 30 (and the attribute "Land Chief Regulation" will be equal to 30).

b. Passive entities

Water sources

Various water sources, randomly distributed in the environment, exist in the agent-based model: wells, drillings and ponds (define by their attribute "nature"). Wells and drillings are permanent water sources, managed by water regulators agents (social entities). These water sources are linked to their water regulator through the attribute "waterRegulator". Ponds are temporary water sources which appear only in the rainy season (the number of ponds created will vary according to the quality of the rainfall). Access to the ponds is free, it does not require to negotiate this access with any regulator.

According to their nature, water sources have different available quantities of water. This value is known by the attribute “waterQuantity”, initially equal to the value of the attributes “initWaterDrillingQuantity”, “initWaterWellQuantity” or “initWaterPondQuantity” according to the nature of the water source. This value is then updated, like the other natural resources, after each rural activity which consumes water and at the beginning of each rainy season where water sources are partially or totally replenished.

Activities

According to the amount of capital they possess, user agents can have up to 6 possible choices of activity: intensive farming, extensive farming, intensive breeding, extensive breeding, intensive NTFP harvesting, and extensive NTFP harvesting. These activities require more or less initial input investment, with a more or less important natural resource consumption and finale production in consequence. It can be associated with water resource in order to improve the yield of already intensive farming or harvesting activities (which become then irrigated intensive activities) (see Table 1). Water is required for breeding activities (a user agent cannot realize these activities without water), or for any rural activity during the dry season (a user agent with no water access right won’t be able to realize activities at this period of the year). At last, extensive farming and harvesting activities which do not require a more permanent water access are only possible during the rainy season (with the rainfall supply). According to the nature of the activity, the nature of the resource consumed on the land plot varies: farming activities consume the fertility of the land plot, breeding activities consume the fodder and harvesting activities consume the NTFP resources.

Each time a user agent realizes a rural activity, a passive located entity is created on the land plot for which the user agent has obtained a resource access right (allowing him to realize this activity). The entity Activity is composed of the attributes:

Attribute	Definition
nature	Defining the nature of the activity
user	linking the activity to the user agent who realize it
localization	Linking the activity to the land plot on which it is realized
quantOfHectares	Defining the number of hectares of the land plot that the activity required
QuantOfResources	Defining the ideal/theoretical quantity of resource (fertility, fodder or NTFP according to the nature of the activity) needed for the activity
effectiveQuant	Defining the real quantity of resource consumed according to the availability of resources on the land plot
WaterNeeded	Defining the ideal/theoretical quantity of water needed for the activity
WaterAvailable	Defining the real quantity of water consumed according to the availability of water of the water source
CapitalNeeded	Defining the investment needed to realize the activity
sourceOfReg	Defining the source of regulation (the regulator agent) allowing the user to realize his activity through the resource access right he delivered to him

Table 1: attributes for the calculation of a rural activity cost and level of production

Activity	Initial Investment (/ha)	Resource consomption (/ha)	Water consomption (/ha)	Productivity rate	Irrigation rate
Intensive Farming	investMinIntensiveFarming	intensiveFertilityConsumptionPerHa	farmingWaterPerHa	intensiveRate	irrigationRate
Extensive Farming	investMinExtensiveFarming	extensiveFertilityConsumptionPerHa		extensiveRate	irrigationRate
Intensive Breeding	investMinIntensiveBreeding	intensiveCattleFodderPerHa	intensiveCattleWaterPerHa	intensiveRate	irrigationRate
Extensive Breeding	investMinExtensiveBreeding	extensiveCattleFodderPerHa	extensiveCattleWaterPerHa	extensiveRate	irrigationRate
Intensive NTFP Harvesting	investMinIntensiveNTFPHarvesting	intensiveGatheringPerHa	nTFPHarvestingWaterPerHa	intensiveRate	irrigationRate
Extensive NTFP Harvesting	investMinExtensiveNTFPHarvesting	extensiveGatheringPerHa		extensiveRate	irrigationRate

For example, if a user realizes an activity of intensive farming on 3 hectares of a land plot, he will initially deduct from his attribute "capital" the value [investMinIntensiveFarming * 3]. He will consume the value: [3* intensiveFertilityConsumptionPerHa] of the fertility of the land plot. If he realizes this intensive farming with a water supply, he will also consume the value: [3*farmingWaterPerHa] of the water of the water source for which he has obtained a water access right. His final production will be equal to: [3* intensiveFertilityConsumptionPerHa * intensiveRate * irrigation Rate], and will be added to his attribute "capital" at the end of the simulation step.

The agent-based model take into account the potential gap between this "ideal", theoretical scenario of activity and the current state of natural resource and water availability. If the quantity of resource on the land plot or on the water source is lower than the user' expectations, he will consume the maximum available at the time of his activity, and his production level will be adapted (and reduced) in consequence.

c. Social entities

Regulators

From the sub-class Regulator, the agent-based model considers 3 possible classes of regulator agents, corresponding to 3 sources of regulation existing within the pluralism of land regulations for securing access to resources:

- the land chief agents, representing the weight of tradition,
- the local community agents, representing the decentralization policy,
- the state agent (central as regionalized).

These regulators represent different rules and laws which exist, or have existed, but which in any case make sense for the users who decide to mobilize them. According to the scenarios the modeler decides to explore, it is possible to introduce into the model up to all of these potential sources of land regulation.

Each regulator agent (Land Chief, Local Community and State) possesses an attribute “resourcesUnderMyRegulation” representing the set of land plots on which he has an administration right. He knows the total size of his territory through the attribute “sizeOfterritory” (equal to the adding of the number of hectares of each land plot of his attribute “resourcesUnderMyRegulation”). For land chief agents, it represents their respective land territories (land plots are linked to their land chief regulator agent through their attribute landChiefTerritory), and for local community agents the decentralized territories they are mandated to manage (land plots are linked to their local community regulator agent through their attribute localCommunity). For the state agent (only one agent of this type created), he always manages the whole territory, known as the state domain (the State knows and is linked to all the land plot of the agent-based model environment, through their attribute “stateplot”). Different regulator agents can have the same land plot to manage on their respective territories, in order to illustrate the overlap of land regulation systems.

Each regulator agent has an attribute “communityOfUsers” allowing him to know the user agents that are part of his landChiefTerritory (if the regulator is a land Chief), his local community (if the regulator is a local Community) or his state domain (if the regulator is the state). As same as for the land plots, the state regulator agent knows all the users of the agent-based model environment, and a same user is attached to a landChiefterritory and to a localCommunity (and to the State) at the same time.

Each regulator agent has an attribute “logic of action” defining the logic he will follow to distribute resource access rights on the land plots he manage. This attribute can take the value: #economic, #social, #enviroConserv or #enviroResto according to the objective the regulator agent prioritizes (see Table 2).

Table 2: synopsis of the regulator different logics of action

Objective	Logic of action
#economic	The focus for allocating resource access rights is here made on users' capital, regulator agents favoring requests of the users with the highest capital
#social	The focus for allocating resource access rights is here made on users themselves. A regulator agent following this logic will adapt his access authorizations to the assurance that all the users of his territory have at least one resource access right
#enviroConserv	The focus for allocating resource access rights is here made on the conservation of resources environmental state. A regulator agent following this logic will close the access to the land plots of his territory where the state of the resources is the best to optimize their environmental durability
#enviroResto	The focus for allocating resource access rights is here made on the restauration of resources environmental state. A regulator agent following this logic will close the access to the land plots of his territory where the state of the resources is the worst, to allow their fastest and better reconstruction.

Endowed with his own logic of action, each regulator agent manages for every season the resource access rights on the land plots of his territory (see Figure 3). When a regulator agent finally decides to give a resource access right on a land plot to a user agent, he gives him an OrderedCollection composed of:

Detail of a resource access right:	**#social**	**#economic**	**#enviroConserv**	**#enviroResto**
A nature of resource access right	Randomly chooses between #rightToUse and #rightToInvestInTheUse. The agent-based model focuses on these two levels of the bundles of rights because it represents two forms of space appropriation already highly differentiated, which impact the decision of investment for the users			
A surface, in hectares, localized on one or several land plot(s)	Equal to the value of the attribute "SocialOptimalSize"	Equal to the value of the user request	Equel to the value of the attribute "EnviroOptimalSize"	
A period	Randomly chooses between: #drySeason, #rainySeason and #annual			
A duration	Randomly chooses between a range of duration (from the season up to several years)			
A access price	Equal to the value of the regulator attribute "rentingPriceCommunity"			

Note here that when user agents make land right requests to regulator agents, they ask for a defined land plot, a defined surface and a defined nature of access right, resulting from the choice of activity they are planning to realize. All the user requests are collect and known by a regulator agent through his attribute "usersRequests". According to their own logics of action, regulators will choose to follow the users wishes, or decide themselves which land plot will be allocate, for which surface, which period, duration, and for what purpose (to use only, or right to invest in the use). All the resource access rights delivered by a regulator agent are kept in his attribute: "accessRightsDelivered".

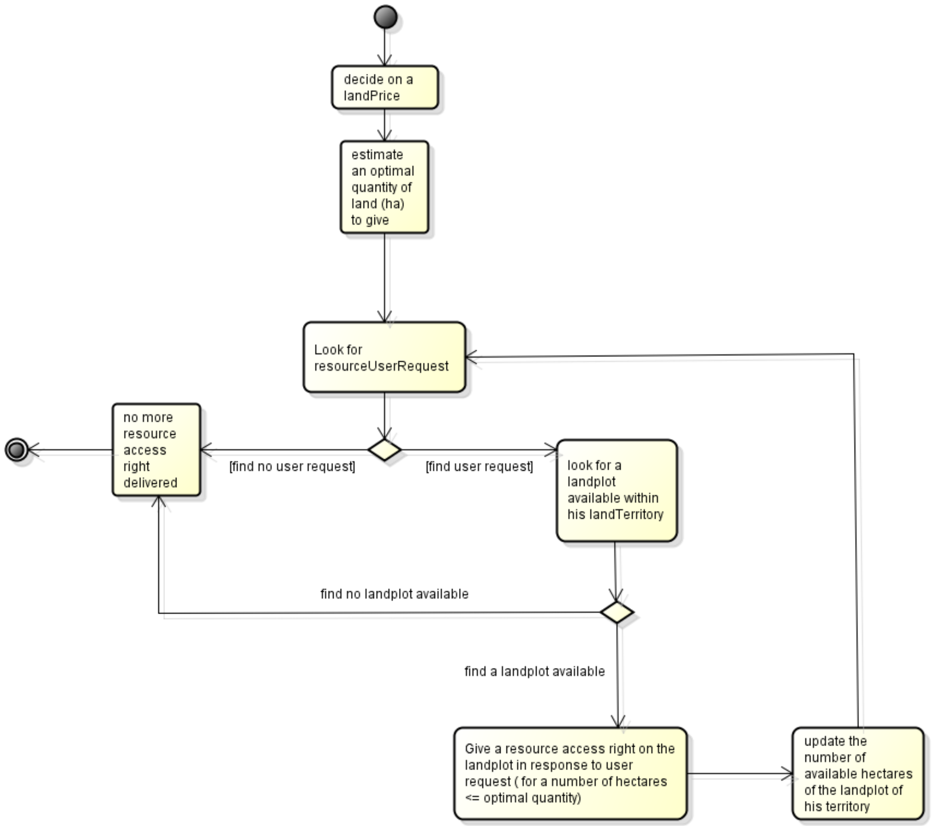


Figure 3: activity diagram for a land regulator and details of its different logics of action according to the objective he prioritizes

Choice of logic of action	**Decide on a unit value (/ha) for his attribute “rentingPriceCommunity”**	**Estimate an optimal quantity of land to allocate**	**Look for resourceUserRequest**	**Look for an available land plot**
#social	Allocates only free lending	SocialOptimalsize = (regulator territory size) / (number of users requests)	Selects a user from a social ranking of the user requests, prioritizing in the first part the ones with no (or few) resource access rights	Considers all the land plots of his territory for which the attribute availableHa >0
#economic	Randomly chooses between a range of unit prices	Follows the users wishes in their requests	Selects a user from a wealth ranking of the user requests prioritizing in the first part the ones with a high amount of capital	
#enviroConserv		EnviroOptimalSize = (Number of land plots with low fertility) / (Number of user of the regulator community)	Selects randomly a user from the user requests	Considers only the land plots with low fertility and with

				availableHa > 0
#enviroResto		EnviroOptimalSize = (Number of land plots with high fertility) / (Number of user of the regulator community)		Considers only the land plots with high fertility and with availableHa > 0

Water Regulators

Each water regulator agent created in the agent-based model has in management one water source (well or drilling) known through his attribute "WaterSourceUnderRegulation". As same as for the land regulators, he regulates for every season the water access rights on his water source, endowed with his own logic of action (see Table 3).

Table 3: synopsis of the water regulator different logics of action

Value of the attribute	Logic of action
#economic	The focus for allocating water access rights is here made on users' capital, regulators favoring requests of the users with the highest capital
#social	The focus for allocating water access rights is here made on users themselves. A regulator following this logic will adapt his access authorizations to the assurance that all the users who have requested a water access from his water source have at least one water access right
#enviro	The focus for allocating water access rights is here made on water environmental state. The regulator following this logic will close the access to his water source when the water level goes below a certain environmental level.

When a water regulator agent decides to distributed a water access right to his water source, this access right is constituted:

- of a certain quantity of water, representing what the user is allowed to take, and define according to the water regulator logic of action;
- for a duration: define by the water regulator attribute "waterRightDuration"
- at a certain cost, known through the water regulator attribute "waterPrice" and defined by the water regulators according to his logic of action.

As with land regulators, when user agents make water right requests to water regulator agents, they ask for a defined water quantity resulting from the choice of activity they are planning to realize. These requests are collect through the water regulator attribute "userWaterRequests". According to their own logics of action, water regulators will choose to follow the users' wishes, or decide themselves which water quantity they allow. All the water access rights delivered by a water regulator agent are kept in his attribute: "waterAccessRightsDelivered".

For both steps, water regulator agents do a succession of actions for distributing water access rights on their water sources, the conditions linked to the realization of these actions depending on the logics they choose to follow (see Table 4).

Table 4: activity diagram for a water regulator and details of its different logics of action according to the objective he prioritizes

Choice of logic of action	Decide on a WaterPrice (/unit of water)	Estimate an optimal quantity of water to distribute	Look for WaterUserRequest
#social (see Figure 4)	Allocates only free water access right	(water source total quantity of water) / (number of users requests)	Selects a user from a social ranking of the user requests prioritizing first the ones with no (or few) water access right
#economic (see Figure 5)	Randomly chooses between a range of unit prices	Authorize the quantity users request while the water source quantity >0	Selects a user from a wealth ranking of the user requests prioritizing first the ones with a high amount of capital
#enviro (see Figure 6)		Authorize the quantity the users request while the water source quantity is higher than one third of the initial water source quantity (in relation with the water source nature)	Selects a user randomly from the user requests

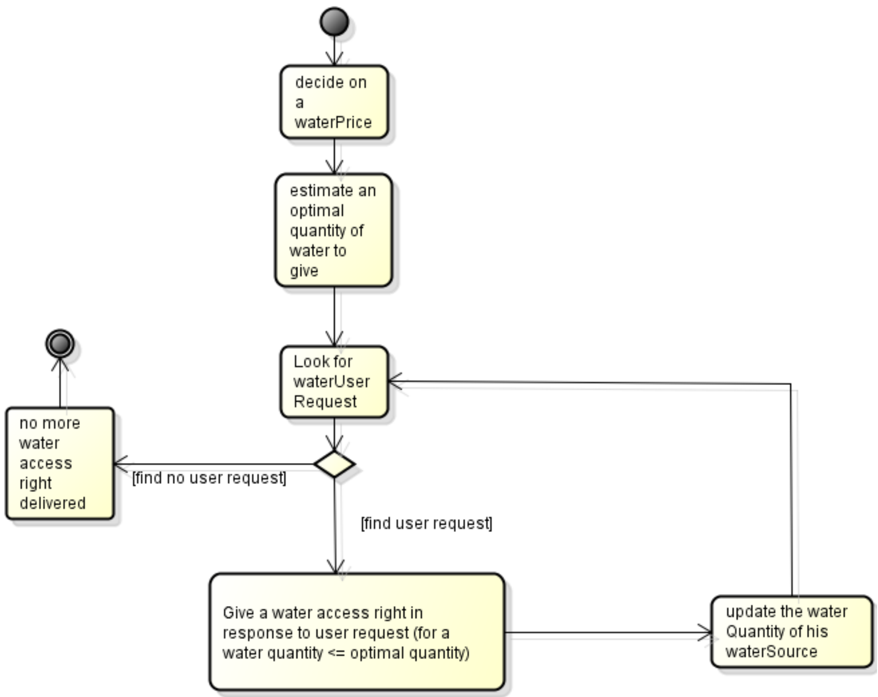


Figure 4: activity diagram for a water regulator prioritizing social objectives

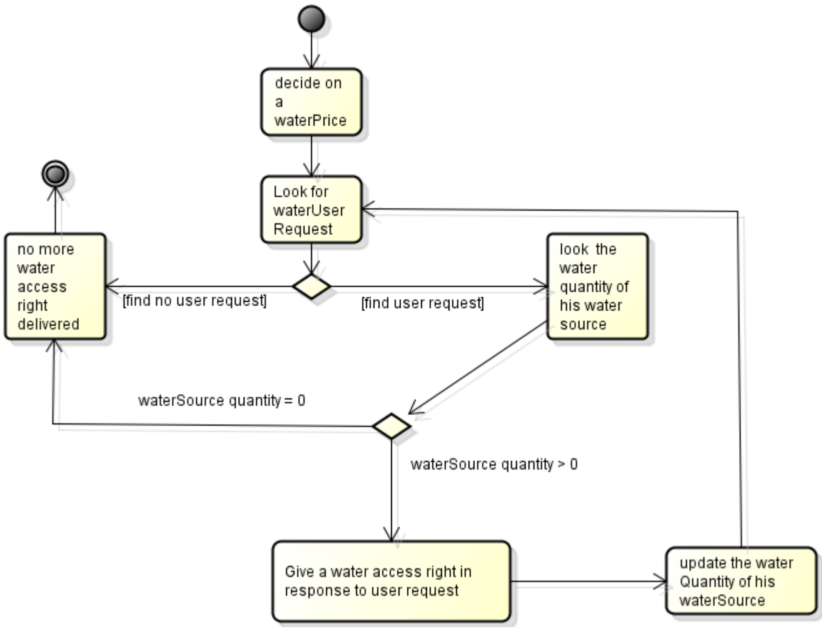


Figure 5: activity diagram for a water regulator prioritizing economic objectives

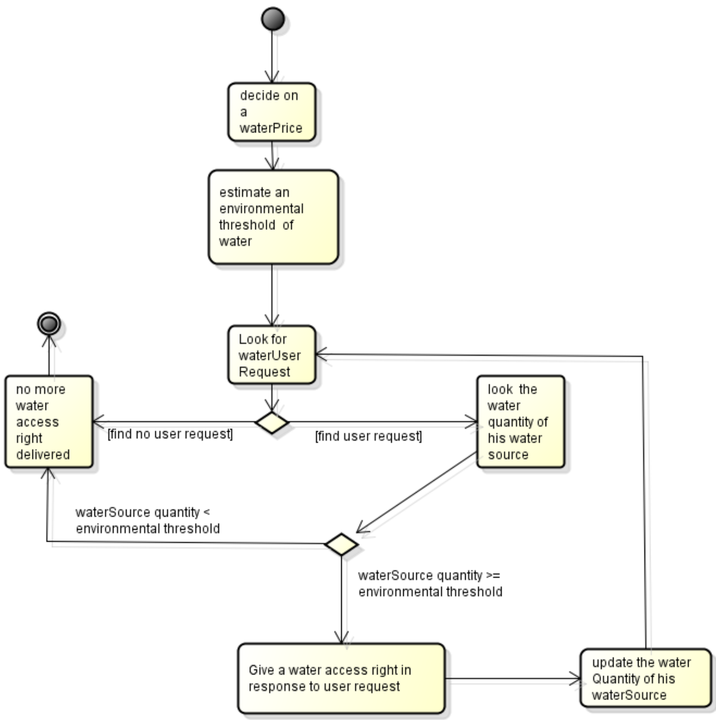


Figure 6: activity diagramm of a water regulator prioritizing environmental objectives

Users

In the agent-based model, three natures of user agent are represented: a rural family, a village or a group of villages, according to the scale analysis of the pluralism of land regulation that the modeler wants to explore. According to his nature, a user agent will have more or less important values of his attributes “collectiveMembers”, “foodSelfSufficiencyThreshold” and “capital” (this attribute symbolizes the gathering of the physical capital, the human capital and the financial capital). User agents created are initially randomly localized in the model environment, and by doing so attached to a land territory (linked to a land Chief agent through their attribute "landChiefTerritory"), a local community (linked to a local community agent through their attribute "localCommunity"), and to the state domain (the state agent knows all the users).

At the beginning of the dry and the rainy seasons (see Figures 7 and 8), user agents start by choosing a first potential activity to realize according to their capital. To do so, they look on their attribute "libraryOfActivities" to select the most intensive activity they can realize (by comparing the different values of initial investment per ha of the activities of the Library with the value of their own capital). Then, they ask (if necessary to their activity) for water access rights to the regulator of the water sources they perceive. To do so, they look around them according to their individual value of attribute "perceptionOfResourceRegulation" (it defines the extent of the water sources they consider) where are the water sources which the higher quantity of water, and they send a request to each of the water regulator linked to the concerned water sources. Requests of a user agent are collect through his attribute "waterAccessRightRequests". Responses from the water regulators (according to their own logics of action) are available through the user attribute "waterAccessRights". According to these responses, user agents will maintain their first choice of activity, or opt for a new one which does not require a water supply (this action is possible only during the rainy season, otherwise a user agent with no water access rights is not able to realize any rural activity). To do so, they look on their attribute "libraryOfActivitiesNoWater".

The choice of activity will lead to a need of a certain number of hectares to realize it (known by the attribute "hectaresNeeded"). This number of hectares is calculated in the agent-based model from the operation: [capital of the user / (initial investment per ha of the chosen activity)]. A user agent always begins by consulting his portfolio of resource access rights (through his attribute "resourceAccessRights"), to know (1) if he already possess available resource access rights, and (2) if these rights are suited and/or sufficient (in term of number of hectares for example, or of nature of access right) with regard to the activity he decided to realize. If his portfolio of resource access rights is empty, unsuitable or simply insufficient, the user agent is going to ask for a new resource access right and by doing so enter in interaction with a source of land regulation.

According to the nature of the chosen activity, a need to reach the natural resources (fertility for farming, NTFP for harvesting, fodder for breeding) is necessary. Users ask for this access to the regulators who manage the resources they request. To do so, they look around them according to the individual value of their attribute "perceptionOfResourceRegulation" (it defines the extent of the land plots they consider) where are the resources with the higher quantity and they send a request to the prevalent land regulator linked to each land plot they have found. This prevalence is known through a ranking by the user agent of the values of the land plot attributes: "Land Chief Regulation", "Local Community Regulation", "State Regulation" and "Other User Regulation". This action symbolizes the fact that a user who wants to access a resource will base his decision on the ways the other users that already exploit the spaces which interest him have obtained their own access rights. If no prevalent source of regulation emerges from the land plot the user agent needs to access, he will by default consider asking for his access right to the land chief agent of the land plot considered. All the requests of a user agent to land regulators are collect through his attribute "resourceAccessRightRequests".

According to the sources of land regulation mobilized and to the return (favorable or unfavorable) of the land regulators, the user agent find himself with a updated portfolio of resource access rights that will condition his final activity decision and the consumption of natural resources that results. For example, all user agents respect the rule about what the nature of the access right allows them to realize. Intensive activities requiring consequent initial investment are considered only by users with rights to invest in the use. Thus if at the end of the interactions with regulators the users find themselves with simple rights to use, they will reconsider their choices to opt for extensive activities (by looking on their attribute “libraryOfExtensiveActivities”). If a right to invest in the use is obtained, user agents will base their final decisions of investment on their attribute “perceptionOfAccessRightDuration”, specific to each user agent. For any right to invest in the use, if the duration of the access right delivered by the regulator goes below the value of this perception of access right duration, the user will consider the act of investment too risky, and will opt for extensive activities.

Part of the production serves to satisfy the food needs of the family, the village or the group of villages (according to the nature of the user agent), and the potential surplus is put back in the user capital for the following step, or season. At the end of each season, user agents update their portfolio of resource access rights, by removing the rights for which the duration reaches its end.

The last source of land regulation considered in the agent-based model is the inter-users regulation. If a user has available hectares to share on his land plot(s) (only for the ones for which the obtained access is a right to invest in the use), he can allow access to it to the other users, becoming by doing so a regulator. To do so, each user agent possessing rights to invest in the use will compare his own need of hectares (through the value of his attribute “hectaresNeeded”) with the total number of hectares proposed with his land right. If his need of hectares is lower than the total available number of hectares, he will propose the complement to other user agents through his attribute “accessRightAvailableToShare”. All the requests from the other users are collect into the attribute “otherUserRequests”.

User-regulators follow the same logics of action as other regulators to define their access permission, they can choose between: #economic, #social, #enviroConserv and #enviroResto (known through the user attribute “logicOfRegulatorAction”). These logics symbolize the various manners to make land circulate between users, through lend (free access), rent (paying access), or through fallow dynamics (close the access to allow the fertility of the land to regenerate) (see Table 5).

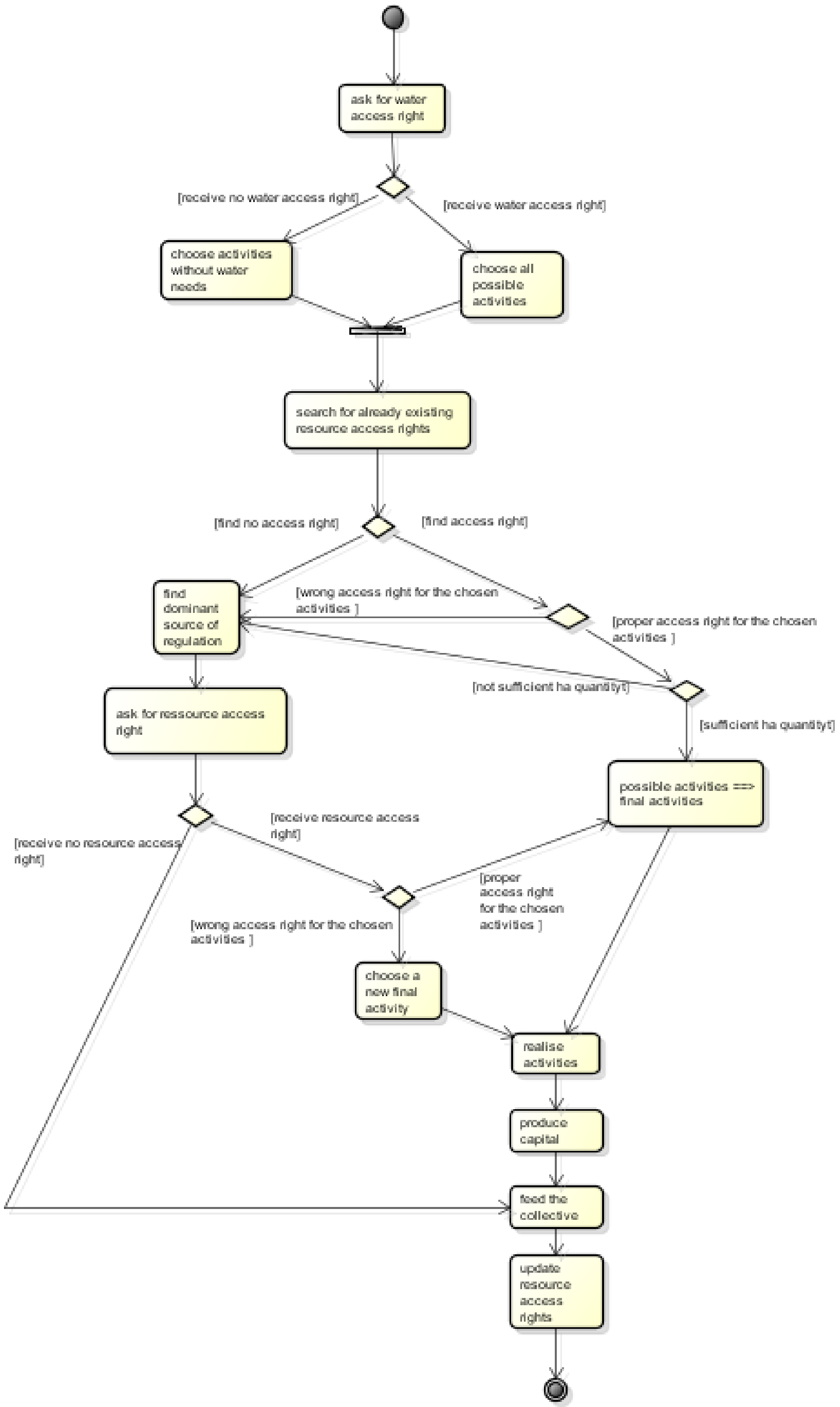


Figure 7: diagram activity of a user agent for the step rainy season

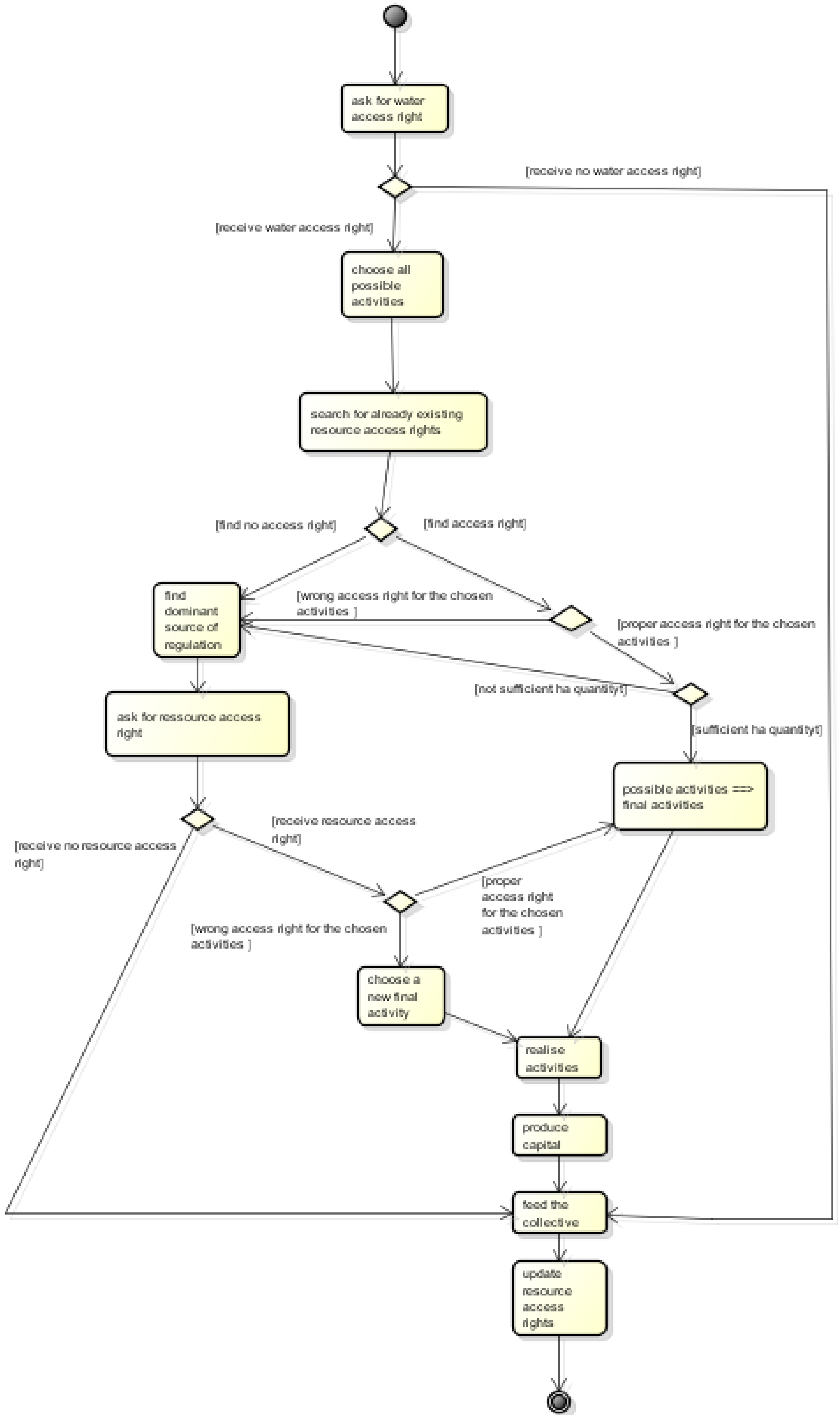


Figure 8: diagram activity of a user agent for the step dry season

Table 5: details of a user-regulator different logics of action according to the objective he prioritizes

<table>
<tr><th>Choice of logic of action</th><th>Decide on a renting Price</th><th>Estimate an optimal quantity of land to allocate</th><th>Select a user from the otherUserRequests</th></tr>
<tr><td>#social</td><td>Defined by the user attribute “socialRentingPrice”</td><td rowspan="4">Adjusts the users wishes in their requests to the number of hectares available (if the number of hectares requested by a user is lower than the total hectares available, the user-regulator will follow the user wishes, if not, he will give him the maximum of hectares still available)</td><td>Selects a user from a social ranking of the other user requests, prioritizing in the first part the ones with no (or few) resource access rights</td></tr>
<tr><td>#economic</td><td>The renting price is calculated by the adding of the price/ha of the initial land right (that the user-regulator first received) with an individual interest rate known through the attribute “interestRate”</td><td>Selects a user from a wealth ranking of the other user requests prioritizing in the first part the ones with a high amount of capital</td></tr>
<tr><td>#enviroConserv</td><td rowspan="2">The renting price is equal to the price/ha of the initial land right (that the user-regulator first received)</td><td rowspan="2">Selects randomly a user from the other user requests</td></tr>
<tr><td>#enviroResto</td></tr>
</table>

When a user-regulator agent decides to give a resource access right to another user, the access right is constituted of the same elements as for the other regulators, but the access right is on his own land plot(s), and the duration is only for one step (a seasonal access right). All the land rights distributed by a user-regulator to other users are collect through his attribute “accessRightDeliveredToUsers”.

d. *Dynamics of the agent-based model*

Agro-ecological dynamics

Natural resource replenishment is linked to the annual rainfall, which is based on the Sahelian concepts of high variability and uncertainty regarding natural resources evolution and availability. In addition to the nature of the environment, the quality (good, medium or bad) of the rainfall has an impact on the environmental state of fertility, fodder, and NTFP on each land plot.

At the beginning of each rainy season, the agent-based model randomly chooses the quality of the rainfall (defining the value of its class attribute rainfallLevel: #good #medium #bad) with a respective probability of 1/6 for the good rainfall, 1/3 for the medium rainfall and ½ for the bad rainfall. According to the quality of this rainfall, the number of land plots for which the natural resource are totally (highRate attribute) or partially (mediumRate: 50%, lowRate: 25%, or zeroRate: 0% of replenishment) replenished will vary (see Table 6). The rate of replenishment is based on the initial quantity of natural resources which differ according to the land type of the land plot (attribute lowlandSoilPerHaInit", "degradedSoilPerHaInit" or "sandySoilperHaInit).

For example, if the rainy season is a good annual rainfall, the agent-based model will randomly select:

- numberOfHighRateGoodRainfallLevel land plots for which, according to their land type, the quantity of each natural resource (fertility, fodder, NTFP) will be recovered with a high rate of 100% of their initial value;
- numberOfMediumRateGoodRainfallLevel land plots for which, according to their land type, the quantity of each natural resource will be recovered with a medium rate of 50% of their initial value;
- numberOfLowRateGoodRainfallLevel land plots for which, according to their land type, the quantity of each natural resource will be recovered with a low rate of 25% of their initial value;
- numberOfZeroRateGoodRainfallLevel land plots for which the quantity of each natural resource will not be recovered.

Table 6: Attributes for the number of land plots served by each level of rainfall according to the quality of the annual rainfall

	Number of land plots with a high rate of replenishment	Number of land plots with a medium rate of replenishment	Number of land plots with a low rate of replenishment	Number of land plots with a zero rate of replenishment
On a **good** annual rainfall *(one in six chance)*	numberOfHighRateGoodRainfallLevel	numberOfMediumRateGoodRainfallLevel	numberOfLowRateGoodRainfallLevel	numberOfZeroRateGoodRainfallLevel
On a **medium** annual rainfall *(one in three chance)*	numberOfHighRateMediumRainfallLevel	numberOfMediumRateMediumRainfallLevel	numberOfLowRateMediumRainfallLevel	numberOfZeroRateMediumRainfallLevel
On a **bad** annual rainfall *(one in two chance)*	numberOfHighRateBadRainfallLevel	numberOfMediumRateBadRainfallLevel	numberOfLowRateBadRainfallLevel	numberOfZeroRateBadRainfallLevel

Land dynamics

Each regulator agent manages a more or less wide territory, on which he distributes at each season resource access rights. During the step, each time a regulator give a resource access right to a user on a certain plot, for a certain surface (ha) and a certain duration, these surface is subtracted from the value of the attribute "available Hectares" of the concerned land plot and the concerned land regulator for all the duration of the resource access right. For example, if a user receives from the state agent a right to use on 10 hectares for 8 seasons at a spatial scale of 50 hectares for the land plot area, the attribute “availableHaState” takes the value 50-10 = 40 hectares for the next 8 step. At the end of the 8th step, the 10 hectares are re-injected on the value of the attribute availableHaState of the land plot, and therefore made available again for the users for future requests.

Note here that this dynamic does not apply to user-regulator agents because they necessarily distribute a seasonal resource access rights which lasts only one step. They indeed decide at each beginning of step if they are going to exploit by themselves their land plot(s), or if they will partially or entirely make these surfaces available to the other user requests. The surfaces exploit through free lend or rent by other users are therefore re-injected to the user-regulators land capital at each end of step.

During the simulation, according to the sources of land regulation the modeler decides or not to introduce, the mobilization of these sources of regulation by the users will potentially evolve, and this will impact the evolution of the number of available hectares of each land regulation sources on the land plots. This dynamic represents in the agent-based model the overlap of land regulation sources. It develops the fact that several users can ask for an access right to the same space and for the same resource, according to the source of regulation they choose to mobilize. We will potentially find in the agent-based model four user agents trying to exploit the resources of the same surface on the same land plot, given for one by a land chief agent, for another by a local community agent, for a third by a user-regulator and for the last one by the state agent.

The agent-based model voluntary does not go beyond this problematic statement. It does not choose if and if so which land regulation source is more important (i.e. which user get to exploit the resources in the end), it is only highlight the overlap, and let the model randomly decides itself.

3. : INITIALISATION OF THE ABM SIMULATIONS

i. Calibration of the simulation

The environment of the agent-based model is composed of 900 land plots. This proportion is fixed (1) in order to authorize the representation of different general spatial scales (according to the value of the land plot area) and (2) in order to control the number of land plot of each land type created, through the class model attributes: numberOfLowLandSoil, numberOfDegradedSoil and numberOfSandySoil. For my set of simulation, the proportion of each land type is equal (300 of each). The lowlands (blue), the intermediary sandy areas (cream) and the degraded lands (pink) are randomly distributed within the environment (see Figure 9), in order to highlight the variability of this Sahelian environment.

Each land plot contains a set of attributes on natural resources: fertility, fodder, and non-timber forest products (NTFP). The initial quantity of each resource is equal to 5 units per hectare if the land plot is a lowland soil, 2 units per hectare if it is a sandy soil and 1 unit per hectare if it is a degraded soil. The total quantity of each natural resource is calculated with regards to the area of the land plot.

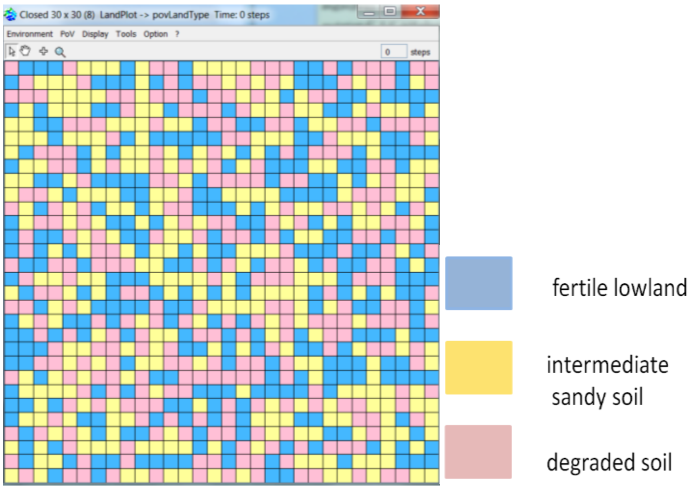


Figure 9: Environment of the agent-based model

In this regard, three choices of initialization exist in the agent-based model, linked to the three possible values of land plot area (see Table 7). If the modeler chooses the INIT A, all the land plot of the environment will have their attribute landPlotArea equal to 1, if he chooses INIT B equal to 50 and if he chooses INIT C equal to 1000. It is not possible during the same simulation to have at the same time a land plot area equal to 1 and another equal to 1000. The idea is that the general landscape represents different

Table 7: three choices of initialization for three space scale representations

Initialization	Land plot Area	Total Area of the environment	Nature of the landscape
INIT A	1 hectare	900 ha / 9 km^2	a village territory
INIT B	50 hectares	45 000 ha / 450 km^2	a set of local communities
INIT C	1000 hectares	900 000 ha / 9000 km^2	a region

Consequently to these three possible choices of Initialization, the number of social and passive entities will also vary (see Table 8).

Table 8: calibration of the three initializations

Initialization	Land plot Area	Number of State agent	Number of Local Community agent	Number of Land Chief agent	Number of User agent
INIT A	1 ha	1	1	5	200 (family level)
INIT B	50 ha	1	5	20	1000 (village level)
INIT C	1000 ha	1	20	56	1000 (group of villages level)

For the particular case of user agents, the equivalence between the space scales is linked to the fact that a user agent does not represent the same social entity at the three scales. The coherence is founded through the combination of the number of user agent created and the value of their attributes collectiveMembers and capital (see Figure 10).

✖ 1000 (5✖200)

✖ 50 (5✖10)

	INIT A	INIT B	INIT C
LANDPLOT AREA (HA)	1	50	1000
NUMBER OF AGENT USER	200 ✖5	1000 ✖5	1000
NUMBER OF COLLECTIVE MEMBER FOR ONE AGENT USER	10 to 20 ✖10	100 to 200 ✖200	2000 to 4000

Figure 10: equivalence of user agent number and attributes according to the choice of space scale

For the INIT A, user agents represent rural families, evolving on the general landscape of a village territory. Every user agent represents a more or less important family: the size of the family known with the attribute “collective members” is randomly initially defined by the agent-based model between a minFamilyMember and a maxFamilyMember attributes, varying from ten to twenty from one user agent to another. This defines consequently the food self-sufficiency threshold to reach for each family. Each user agent has also an attribute “capital”, which symbolizes the gathering of the physical capital, the human capital and the financial capital. The initial value of this capital is randomly defined according to the size of the family: for one user agent, each member of the family has an individual capital value chosen randomly among the values: # (1 5 10 20 50 100 500), and the final initial capital of the user agent is the sum of this various individual capital. The idea is to represent the diversity of production means that different Sahelian rural families can possess.

For the INIT B, user agents represent this time villages (as grouping of several families) evolving on a global landscape equivalent to a set of local communities. For the INIT C, user agents represent groups of several villages, evolving on a global landscape similar to a region. The equivalences in terms of number of user agents created (and of the collective members of each user agent) have been estimated regarding the change of land plot area from one initialization to another. The initialization of the attribute capital for the init B and C follows the same principle as for the init A.

The perception of land tenure security is specific to each user agent, and defined in the agent-based model through the values of the attributes “perceptionOfAccessRightDuration” and “perceptionOfResourceRegulation”. The “perception of access right duration” is varying from 2 up to 10, the value is randomly initially fixed. As a reminder, for any right to invest in the use, if the duration of the access right delivered by the regulator goes below this perception of access right duration, the user will consider the act of investment too risky, and will opt for extensive activities.

The “perception of resources and their regulation(s)” is varying from 1 up to 30 for the INIT A, and from 1 up to 15 for the INIT B and C, and the value is also randomly initially fixed. This reflects the idea that the level of information that land actors possess about land regulations strongly vary from one user to another, some of them have a perception that only extend on their village, or their land territory whereas others will know what is happening in the all country (i.e. the total environment of the agent-based model) (see Figure 11). As a reminder, user agents mobilize this attribute when they look for available land plots which possess the resources they need, it defines the extent of the land plots they consider. The same attribute is used when user agents look for water sources and send water requests to the water regulators of the water sources they found.

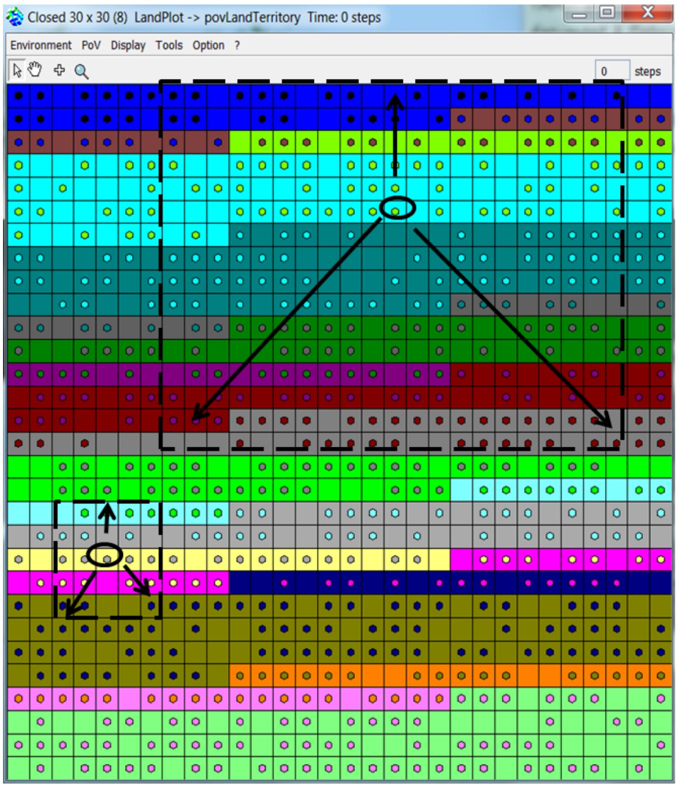


Figure 11: Illustration of the diversity of the levels of perception, reflecting the level of information of the agent user. Level of perception of the lower left user: 2; level of perception of the upper right user: 10. The environment represents the different land territories of the land chief agents

At last, according to the amount of capital they possess, the characteristics of their land access rights, the fact that they can access water or not, user agents can have up to 6 possible choices of rural activity, more or less intensive (see Table 9).

Table 9: calibration of the values of the attributes of the activity passive entities according to the nature of the activity

Activity	Initial Investment (/ha)	Resource consomption (/ha)	Water consomption (/ha)	Productivity rate	Irrigation rate
Intensive farming	50	500	500	10	5
Extensive farming	2	20		2	
Intensive breeding	120	1000	1000	10	
Extensive breeding	6	60	60	2	
Intensive NTFP harvesting	20	250	250	10	5
Extensive NTFP harvesting	1	10		2	

The environment of the model is divided for each type of regulator agent (Land Chief, Local Community and State) in more or less territories according to the type of agent and the choice of Initialization (see Figure 12). For land chief agents, it represents their respective land territories, and for local community agents the decentralized territories they are mandated to manage. For the state agent (only one agent of this type created no matter the choice of Initialization), he always manages the whole territory (known as the state domain).

According to the choice of initialization made, the number of each type of water source (and the number of water regulator agents in consequence), as well as the quantity of water they contain will also not be the same:

Initialization	Number of ponds			Number of wells	Number of drillings
	Good rainfall	Medium rainfall	Bad rainfall		
INIT A	6	3	2	8	1
	Water initial quantity : 100 units			Water initial quantity : 200 units	Water initial quantity : 50 000 units
INIT B	30	15	10	100	30
	Water initial quantity : 1000 units			Water initial quantity : 10 000 units	Water initial quantity : 50 000 units
INIT C	X			X	260
					Water initial quantity : 200 000 units

These water sources are initially (for the well and the drillings) of at each beginning of rainy season (for the pounds) randomly localized in the environment (see Figure 13).

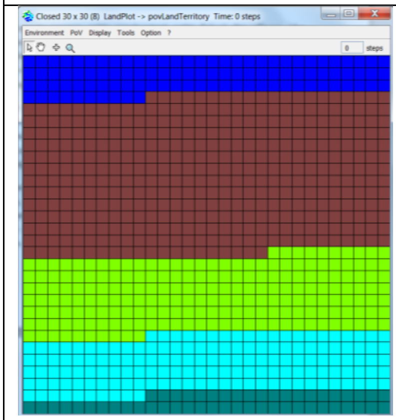
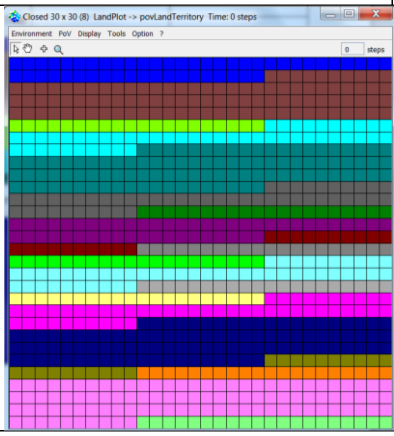
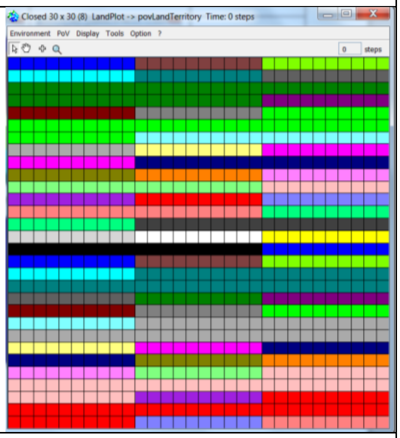
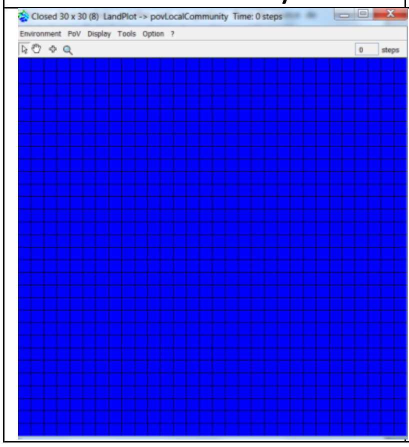
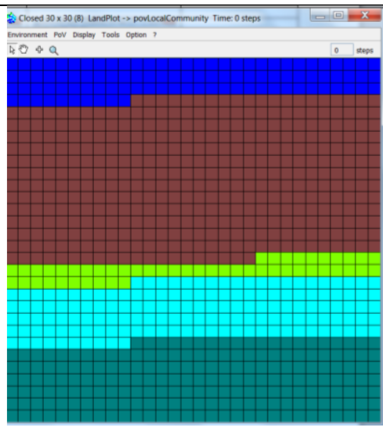
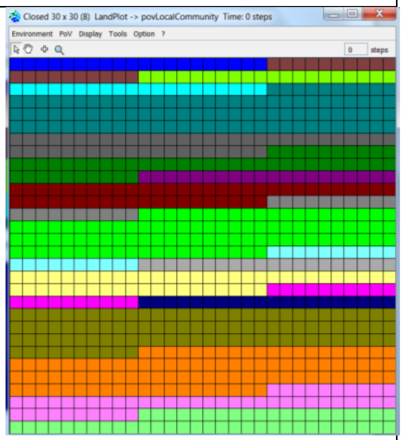
<table>
<tr><th colspan="3">LAND REGULATION SOURCE : LAND CHIEF</th></tr>
<tr><td>INIT A : 5 land chief agents and their territories</td><td>INIT B : 20 land chief agents and their territories</td><td>INIT C : 56 land chief agents and their territories</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><th colspan="3">LAND REGULATION SOURCE : LOCAL COMMUNITY</th></tr>
<tr><td>INIT A : 1 local community agent and his territory</td><td>INIT B : 5 local community agent and their territories</td><td>INIT C : 20 local community agent and their territories</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

Figure 12: configuration of the different regulator agents territories according to the choice of space scale

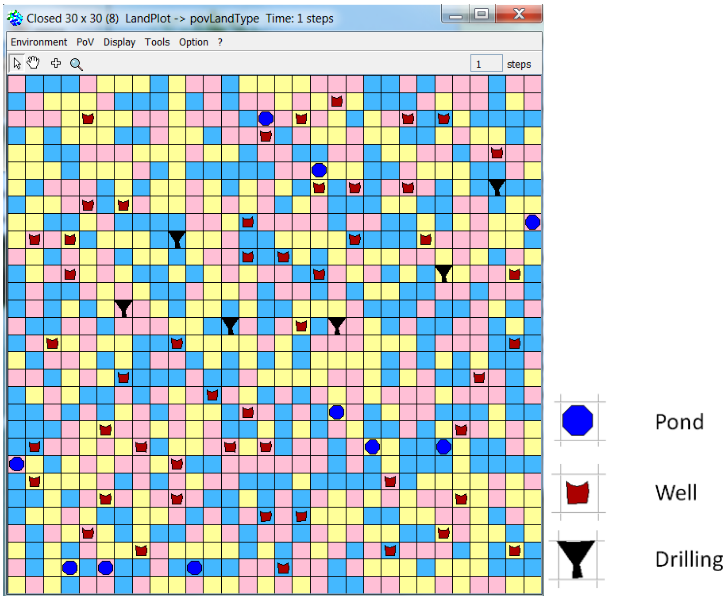


Figure 13: random initial distribution of the water sources passive entities within the environment (INIT B)

Land regulator agents (see Table 10), water regulator agents (see Table 11) and user-regulators ((see Table 12) allocate at each growing season access rights on their territory, water source or land plot(s). The different components of an access right are fixed according to the choice of logic of action.

Table 10: calibration of the different parameters composing a resource access right according to the logic of action of the land regulator agent

Detail of a resource access right:	**#social**	**#economic**	**#enviroConserv**	**#enviroResto**
A nature of resource access right	Randomly chooses between #rightToUse and #rightToInvestInTheUse			
A surface, in hectares, localized on one or several land plot(s)	SocialOptimalsize = (regulator territory size) / (number of users requests)	Follows the users wishes in their requests	EnviroOptimalSize = (Number of land plots with low fertility) / (Number of user of the regulator community)	EnviroOptimalSize = (Number of land plots with high fertility) / (Number of user of the regulator community)
A period	Randomly chooses between: #drySeason, #rainySeason and #annual			
A duration	Randomly selects between #(1 1 1 1 2 2 2 2 6 6 10 20 30 100)		Randomly selects between #(1 1 1 1 2 2 2 2 6 6)	
A access price	rentingPriceCommunity = 0.	rentingPriceCommunity = Randomly selects between: #(5 10 20 50 100)	rentingPriceCommunity = Randomly selects between: #(0 5 10)	

Table 11: calibration of the different parameters composing a water access right according to the logic of action of the water regulator agent

Detail of a resource access right:	**#social**	**#economic**	**#enviro**
Quantity of water	(water source total quantity of water) / (number of users requests)	Authorize the quantity users request while the water source quantity >0	Authorize the quantity the users request while the water source quantity is higher than one third of the initial water source quantity (in relation with the water source nature)
Water Price	waterPrice = 0	waterPrice = Randomly selects between: #(0.05 0.1 0.5 1)	waterPrice = Randomly selects between: #(0 0.05 0.1)
Access Duration	waterRightDuration = 1 (only seasonal water access rights)		

Table 12: calibration of the different parameters composing a resource access right according to the logic of action of the user-regulator agent

Detail of a resource access right:	**#social**	**#economic**	**#enviro Conserv**	**#enviro Resto**
A nature of resource access right	Randomly chooses between #rightToUse and #rightToInvestInTheUse			
A surface, in hectares, localized on one or several land plot(s)	Adjusts the users wishes in their requests to the number of hectares available (if the number of hectares requested by a user is lower than the total hectares available, the user-regulator will follow the user wishes, if not, he will give him the maximum of hectares still available)			
A period	Give the one of the user-regulator access right			
A duration	RentingDuration = 1 (only seasonal land access rights)			
A access price	socialRentingPrice = 0	The renting price is equal to the price/ha of the initial land right (that the user-regulator first received) + (price/ha interestRate). interestRate = Randomly select between: #(0 5 10 20 50)	The renting price is equal to the price/ha of the initial land right (that the user-regulator first received)	

At the beginning of each rainy season, the agent-based model randomly chooses the quality of the rainfall. According to this quality, the number of land plots for which the natural resource are totally (highRate attribute) or partially (mediumRate: 50%, lowRate: 25%, or zeroRate: 0% of replenishment) replenished will vary (see Table 13 and Figure 14).

Table 13: calibration of the rainfall dynamic according to its annual quality

Number of land plots associated to each level rate according to the quality of the rainfall	High Rate (100% of replenishment)	Medium Rate (50% of replenishment)	Low Rate (25% of replenishment)	Zero Rate (0% of replenishment)
For a **good** annual rainfall *(one in six chance)*	300	275	275	50
For a **medium** annual rainfall *(one in three chance)*	75	350	300	175
For a **bad** annual rainfall *(one in two chance)*	0	150	450	300

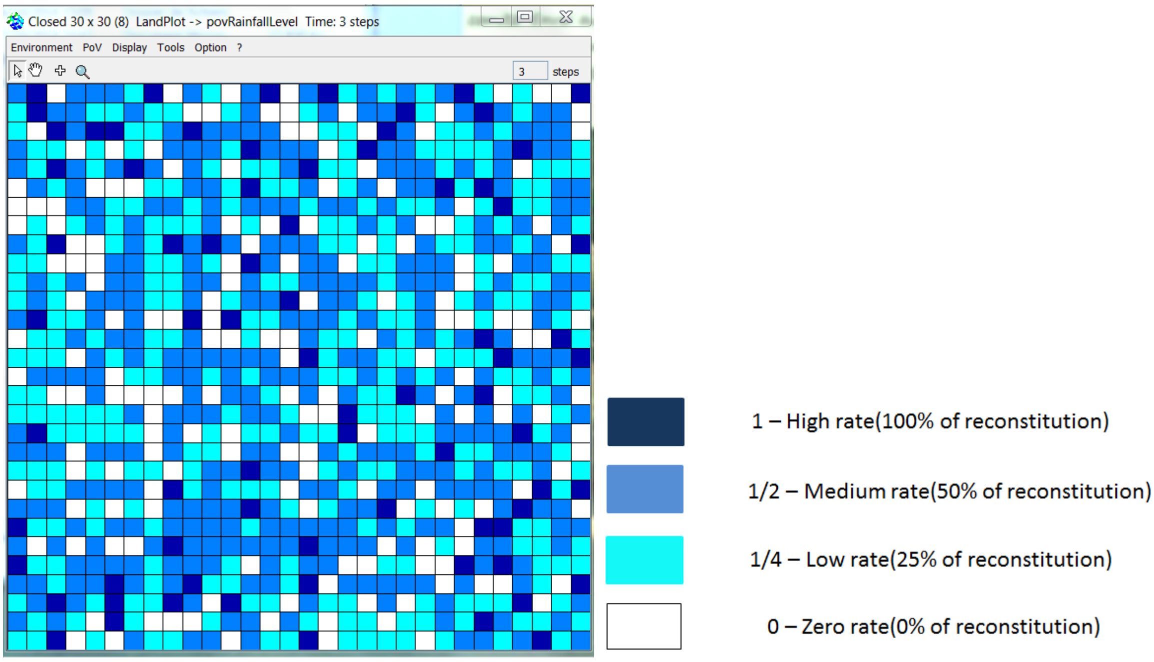


Figure 14: illustration of the rainfall dynamic high spatial variability on a good annual rainfall

ii. Synopsis of the simulation

At the initialization (no matter the choice of INIT), all the environment of the model is divided in land territories managed by default by different land chiefs (representing the historical context, the weight of tradition). User agents are created and randomly localized in this environment (and thus attached to a specific land territory and a local community). Water regulators and their water sources are also created and randomly localized in the environment.

Each land chief agent chooses a certain logic of action, and allocates consequently resource access rights to the users of his land territory. This will constitute their initial "land capital". The other regulator agents (local communities and state) are also created, and linked to a set of land plots (or to the all environment for the state agent), but they are not active for now as land regulators, they do not exist in the user agents perception.

During the simulation, it is possible for the modeler to introduce up to all the land regulation sources, and by doing so activate the State, and/or the local community and/or the user-regulator agents as land regulators. To do so, as explained above, the modeler can modify the value of one or several of the attributes: “Land Chief update”, “Local Community update”, “State update” or “Other User update” of the land plots, according to the source of regulation considered for the scenario. These “update” attributes are by default equal to zero, and it is by modifying the value of these attributes that the modeler can introduce new sources of land regulation in the simulation. It will potentially change de nature of the prevalent source of land regulation on the concerned land plot, and its mobilization by the user agents in consequence.

The time step in the agent-based model is the growing season. A simulation consists of a succession of rainy and dry seasons (one year corresponds thus to two steps) which lasts the number of years considered necessary for the simulated scenario. Both steps (rainy and dry season) take place globally similarly (see Figure 15 and 16). The main difference is that in the beginning of the rainy season, we observe, linked to the rainfall, the reconstitution of natural resources and the formation of ponds whereas at the beginning of dry season, there is no natural resources reconstitution and the ponds disappear.

Besides these ecological dynamics, users begin both steps by asking for water access rights to the water regulators of the various water sources. According to the positive of negative response of the water regulators, users make a first choice of activity. Another specificity of the dry season is that a user with no water access will not be able to realize rural activities at all (any activity necessarily requires water in this period of the year). These choices of activities can lead to a need of natural resources that users ask to the various land regulators. According to what they finally obtained by the land regulators who follow their own logics of action, users will maintain or modify their initial choice of activity, and eventually exploit and consume the various resources of the environment, in order to produce and improve their capital.

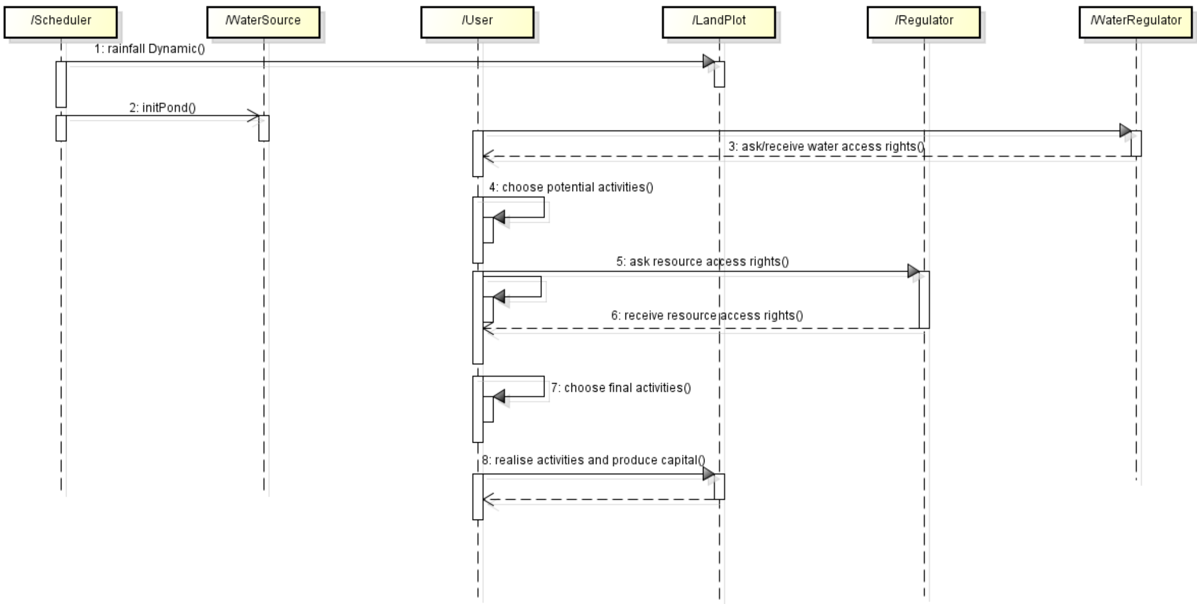


Figure 15: sequence diagram of the rainy season step

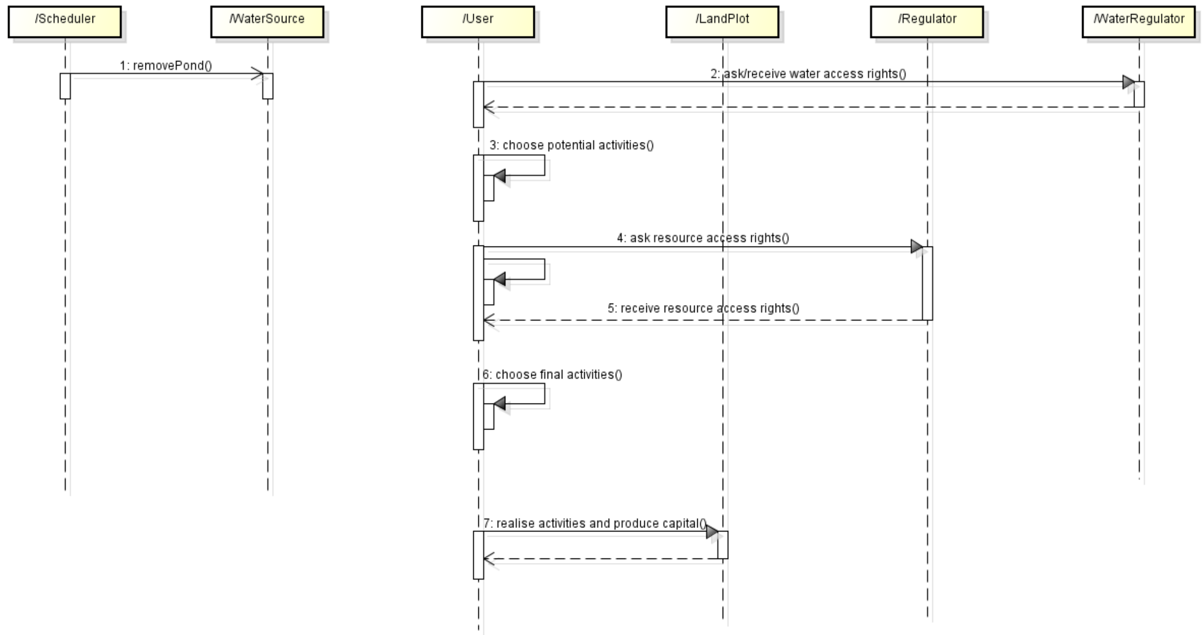


Figure 16: sequence diagram of the dry season step

iii. Indicators

On this basis, according to the choices of scenario implemented, simulations are conducted, with each agent representing one of the various types of actor, developing his logic of action according to his perception and drawing from several overlapping land and natural resource regulation sources at the same time.

The effects resulting from the simulation of land policy options are subsequently deducted from the agents' behaviors (during and at the end of the successive simulations) rather than predetermined by a causal chain of effects. These effects are thus the result of the pooling of actors' various logics of action, which are motivated by their various representations. During and at the end of the simulation, several indicators can allow the operator to explore different aspects of change between the initial situation and the final situation, at the general level of the agent-based model (see Table 14) and at a "local" level of each spatial, social and passive entity (see Table 15).

Table 14: choice of indicators to follow at the general level of the agent-based model

Thematic of the probes	Name of the Probe	Definition of the Probe
Natural resources dynamics **(see Figure 17)**	badRainfallLevel	Record the number of bad annual rainfall during the simulation (i.e. step after step)
	mediumRainfallLevel	Record the number of medium annual rainfall during the simulation
	goodRainfallLevel	Record the number of good annual rainfall during the simulation
	landPlotFertility	Follow the evolution of the general quantity of fertility within all the environment during the simulation
	landPlotFodder	Follow the evolution of the general quantity of fodder within the all environment during the simulation
	landPlotNTFP	Follow the evolution of the general quantity of NTFP within the all environment during the simulation
	drillingWaterQuantity	Follow the evolution of the general quantity of water of all the drillings during the simulation
	wellWaterQuantity	Follow the evolution of the general quantity of water of all the wells all the environment during the simulation
Land regulations dynamics **(see Figure 21 and 22)**	landChiefLevel	Record the number of activities realized by user agents through resource access rights delivered by land chief agents
	landPlotlandChiefAvailableHa	Follow the evolution of the general number of available hectares to allocate for the land chief agents
	landPlotlandChiefRegulation	Follow the evolution of the general number of land plots with users exploiting on it under land chief regulations
	localCommunityLevel	Record the number of activities realized by user agents through resource access rights delivered by local communities agents
	landPlotlocalCommunityAvailableHa	Follow the evolution of the general number of available hectares to allocate for the local community agents
	landPlotlocalCommunityRegulation	Follow the evolution of the general number of land plots with users exploiting on it under local community regulations
	stateLevel	Record the number of activities realized by user agents through resource access rights delivered by the state agent

	landPlotStateAvailableHa	Follow the evolution of the general number of available hectares to allocate for the state agent
	landPlotStateRegulation	Follow the evolution of the general number of land plots with users exploiting on it under state regulations
	otherUserLevel	Record the number of activities realized by user agents through resource access rights delivered by user-regulator agents
	landPlotOtherUserRegulation	Follow the evolution of the general number of land plots with users exploiting on it under user-regulator regulations
	numberOfInterUserAccessRightDelivered	Record the number of resource access rights delivered by user-regulator agents during the simulation
	noneRegulationLevel	Record the number of land plots with no land regulation source management during the simulation *(No land regulator is allocating any access right on these land plots)*
	oneRegulationLevel	Record the number of land plots with one land regulation source management during the simulation *(One nature of land regulator is allocating access rights on these land plots)*
	twoRegulationLevel	Record the number of land plots with two overlapping land regulation sources management during the simulation *(Two natures of land regulator are allocating access rights at the same time on these land plots)*
	threeRegulationLevel	Record the number of land plots with three overlapping land regulation sources management during the simulation *(Three natures land regulator are allocating access rights at the same time on these land plots)*
User access rights and activities dynamics **(see Figure 20)**	userCapital	Follow the evolution of the general capital of all user agents during the simulation
	extensiveBreedingLevel	Record the number of users realizing extensive breeding during the simulation
	intensiveBreedingLevel	Record the number of users realizing intensive breeding during the simulation
	extensiveFarmingLevel	Record the number of users realizing extensive farming during the simulation
	intensiveFarmingLevel	Record the number of users realizing intensive farming during the simulation
	extensiveNTFPHarvestingLevel	Record the number of users realizing extensive NTFP Harvesting during the simulation
	intensiveNTFPHarvestingLevel	Record the number of users realizing intensive NTFP Harvesting during the simulation

	numberOfLandPlotUsers	Record the number of land plots with user agents possessing access rights on it during the simulation
	numberOfUsersWithActivities	Record the number of users who realize activities during the simulation
	numberOfUsersWithResourceAccessRights	Record the number of users with resource access rights in their portfolio during the simulation
	numberOfUsersWithResourceAccessRequests	Record the number of users with resource access rights requests during the simulation
	numberOfUsersWithWaterAccessRights	Record the number of users with water access rights in their portfolio during the simulation
	numberOfUsersWithWaterAccessRequests	Record the number of users with water access rights requests during the simulation

LEGEND
Attributes for the calculation of the probe are associated to spatial entities
Attributes for the calculation of the probe are associated to social entities
Attributes for the calculation of the probe are associated to passive entities
The calculation of the probe is associated to attributes at the agent-based Cormas model level

Table 15: choice of indicators to follow at the entities local level of the agent-based model

Thematic of the probes	Name of the Probe	Definition of the Probe
User agent	collectiveMembers	Inform the modeler of the number of members of each user agent (family, village or group of villages)
	foodSelfSufficiencyThreshold	Inform the modeler of the food self-sufficiency threshold of each user agent according to the number of its collective
	logicUserRegulator	Inform the modeler of the logic of action follow by each potential user-regulator
	numberOfAccessRights	Inform the modeler of the number of resource access right each user agent possesses during the simulation (i.e. step after step)

	numberOfAccessRightRequests	Inform the modeler of the number of resource access right each user agent requests during the simulation
	numberOfAccessRightAvailableToShare	Inform the modeler of the number of access right to his land plot each user agent makes available to other user agents during the simulation
	numberofOtherUserAccessRightDelivered	Inform the modeler of the number of access right to his land plot each user agent delivers to other user agents during the simulation
	numberofOtherUserRequests	Inform the modeler of the number of access right requests each user-regulator agent receives from other user agents during the simulation
	numberOfWaterAccessRights	Inform the modeler of the number of water access right each user agent possesses during the simulation
	numberOfWaterAccessRequests	Inform the modeler of the number of water access right each user agent requests during the simulation
LandChief agent	Logic (see Figure 18)	Inform the modeler of the logic of action follow by each land chief agent
	numberOfUsersDeliveredLandChief	Inform the modeler of the number of resource access right each land chief agent delivers to user agents during the simulation
	numberOfUsersRequestsLandChief	Inform the modeler of the number of resource access right requests each land chief agent receives from user agents during the simulation
LocalCommunity agent	Logic (see Figure 18)	Inform the modeler of the logic of action follow by each local community agent
	numberOfUsersDeliveredLocalCommunity	Inform the modeler of the number of resource access right each local community agent delivers to user agents during the simulation
	numberOfUsersRequestsLocalCommunity	Inform the modeler of the number of resource access right requests each local community agent receives from user agents during the simulation
State agent	Logic (see Figure 18)	Inform the modeler of the logic of action follow by the state agent
	numberOfUsersDeliveredState	Inform the modeler of the number of resource access right the state agent delivers to user agents during the simulation
	numberOfUsersRequestsState	Inform the modeler of the number of resource access right requests the state agent receives from user agents during the simulation
Water regulator agent	Logic (see Figure 19)	Inform the modeler of the logic of action follow by each water regulator agent
	numberOfWaterAccessDelivered	Inform the modeler of the number of water access right each water regulator agent delivers to user agents during the simulation
	numberOfWaterAccessRequests	Inform the modeler of the number of water access right requests each water regulator agent receives from user agents during the simulation

Landplot	activitiesOnTheLandPlot	Inform the modeler of the number of ongoing activities on each land plot during the simulation
	usersOfTheLandPlot	Inform the modeler of the number of user agents with ongoing resource access right on each land plot during the simulation
	Fertility	Inform the modeler of the evolution of fertility quantity on each land plot during the simulation
	Fodder	Inform the modeler of the evolution of fodder quantity on each land plot during the simulation
	NTFP	Inform the modeler of the evolution of NTFP on each land plot during the simulation
WaterSource	waterQuantity	Inform the modeler of the evolution of water quantity on each water source during the simulation

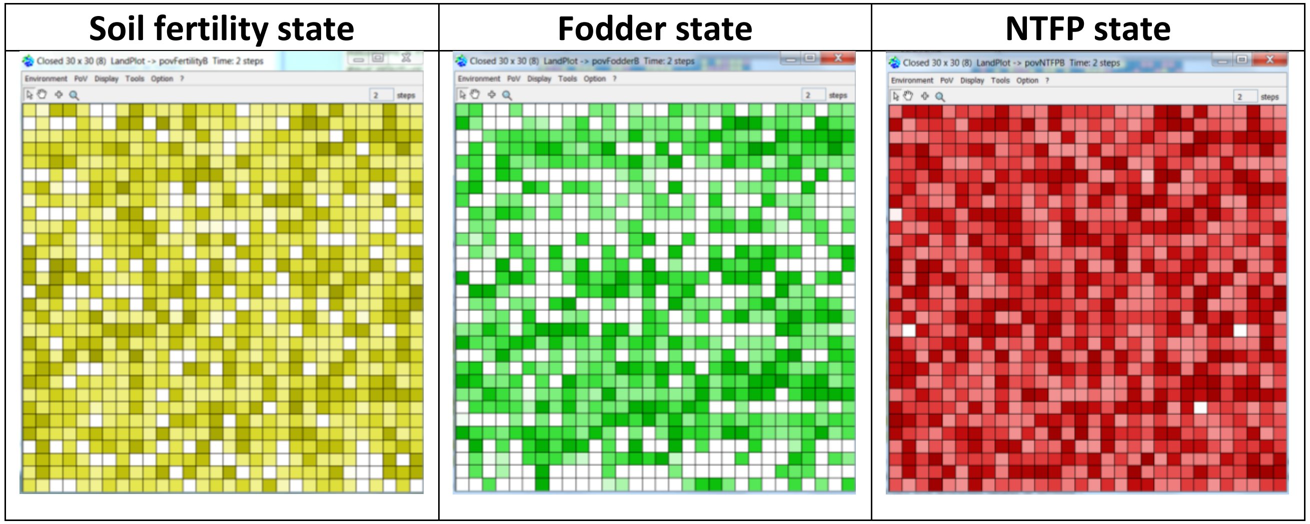


Figure 17: diversity of environmental state of natural resources according to the land type

Figure 18: illustration of land regulators diversity of logics of action for one simulation

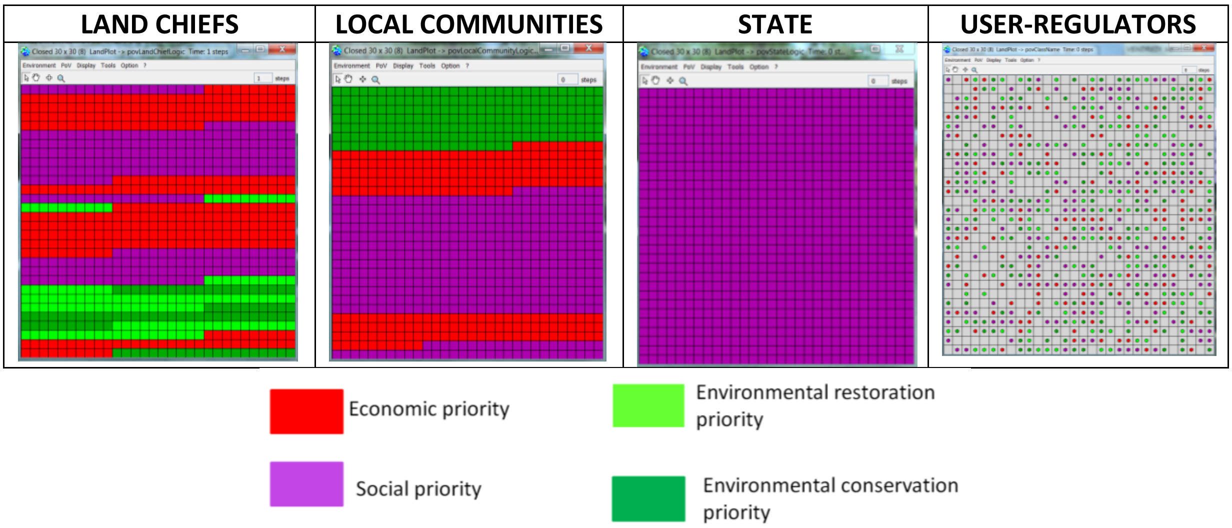
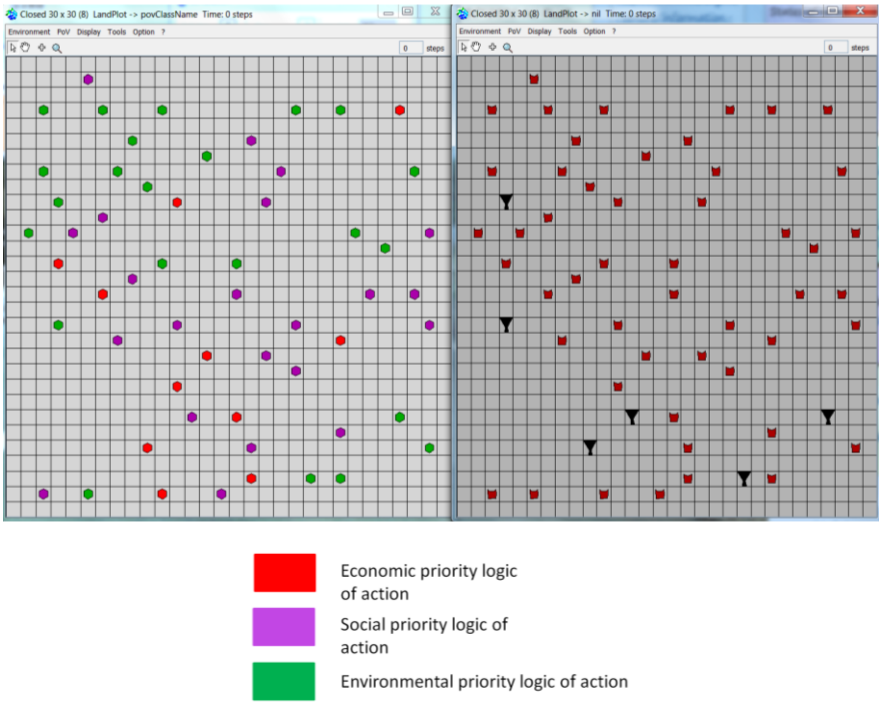


Figure 19: illustration of water regulators diversity of logics of action for one simulation



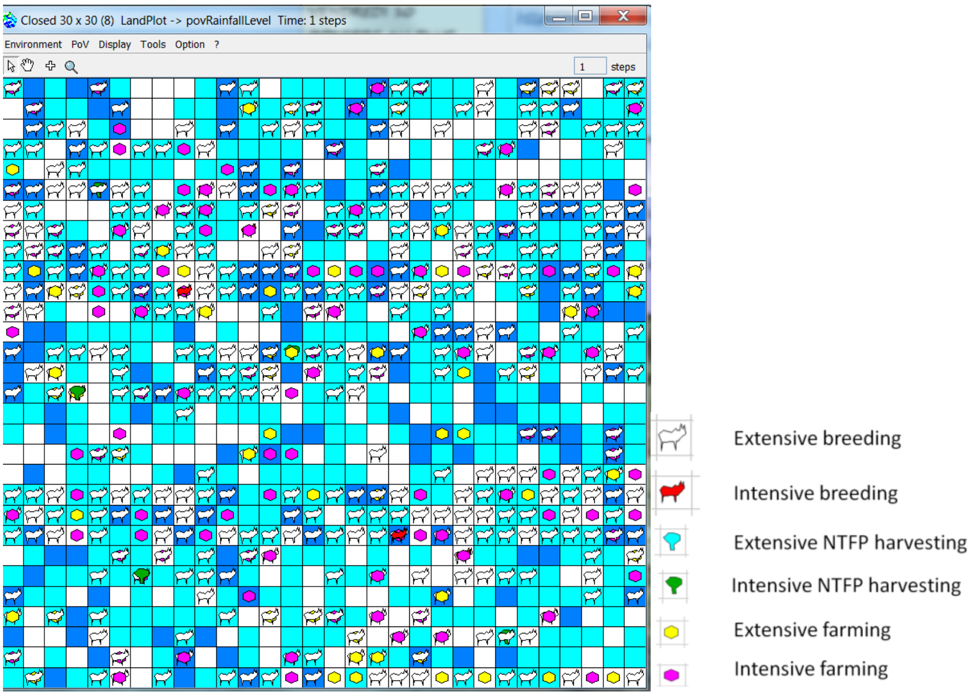


Figure 20: illustration of the plurality of user activities during a rainy season of a simulation

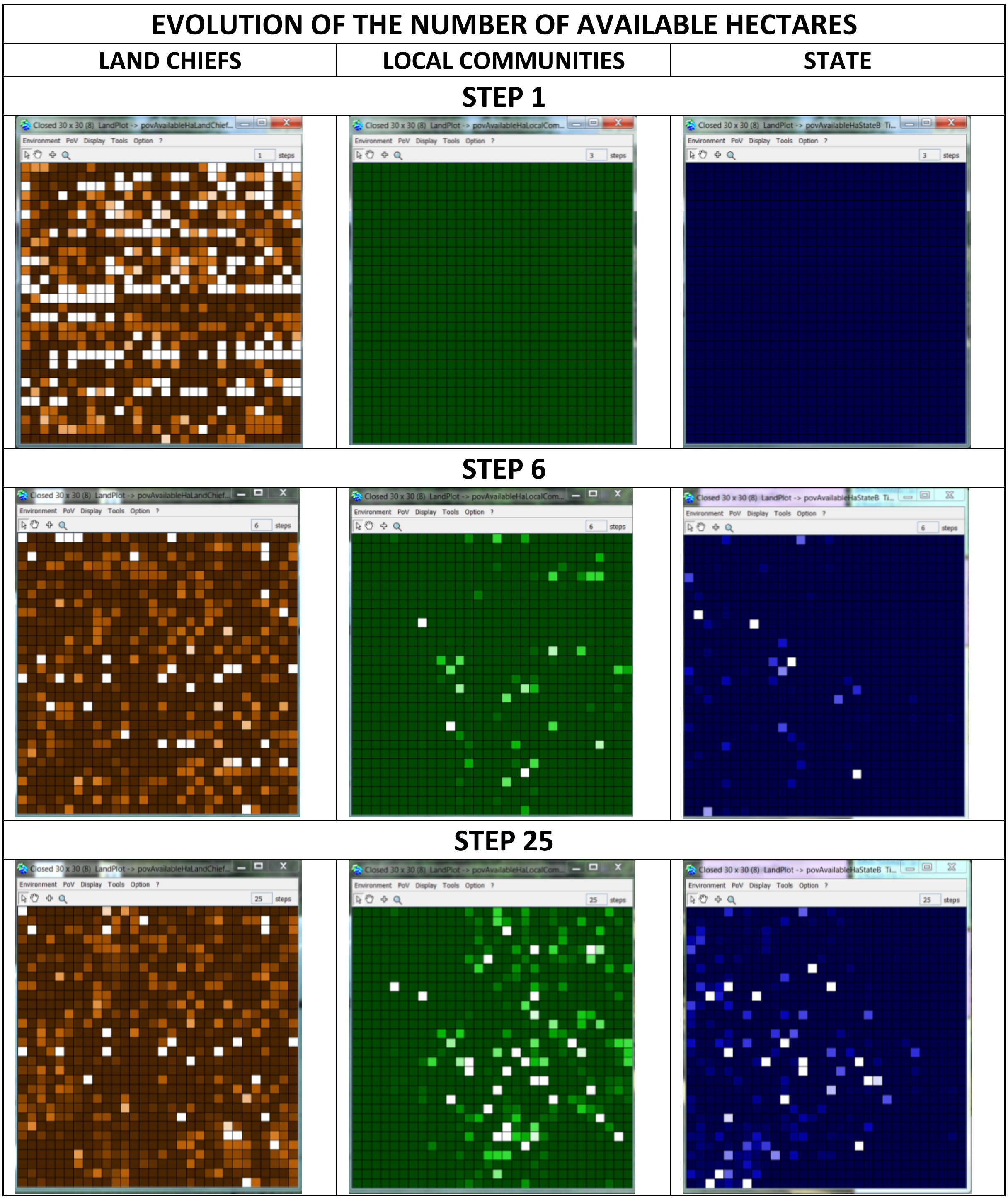


Figure 21 : land dynamics and evolution of the number of hectares available for each type of land regulator agent once new sources of regulation are introduced in the simulation

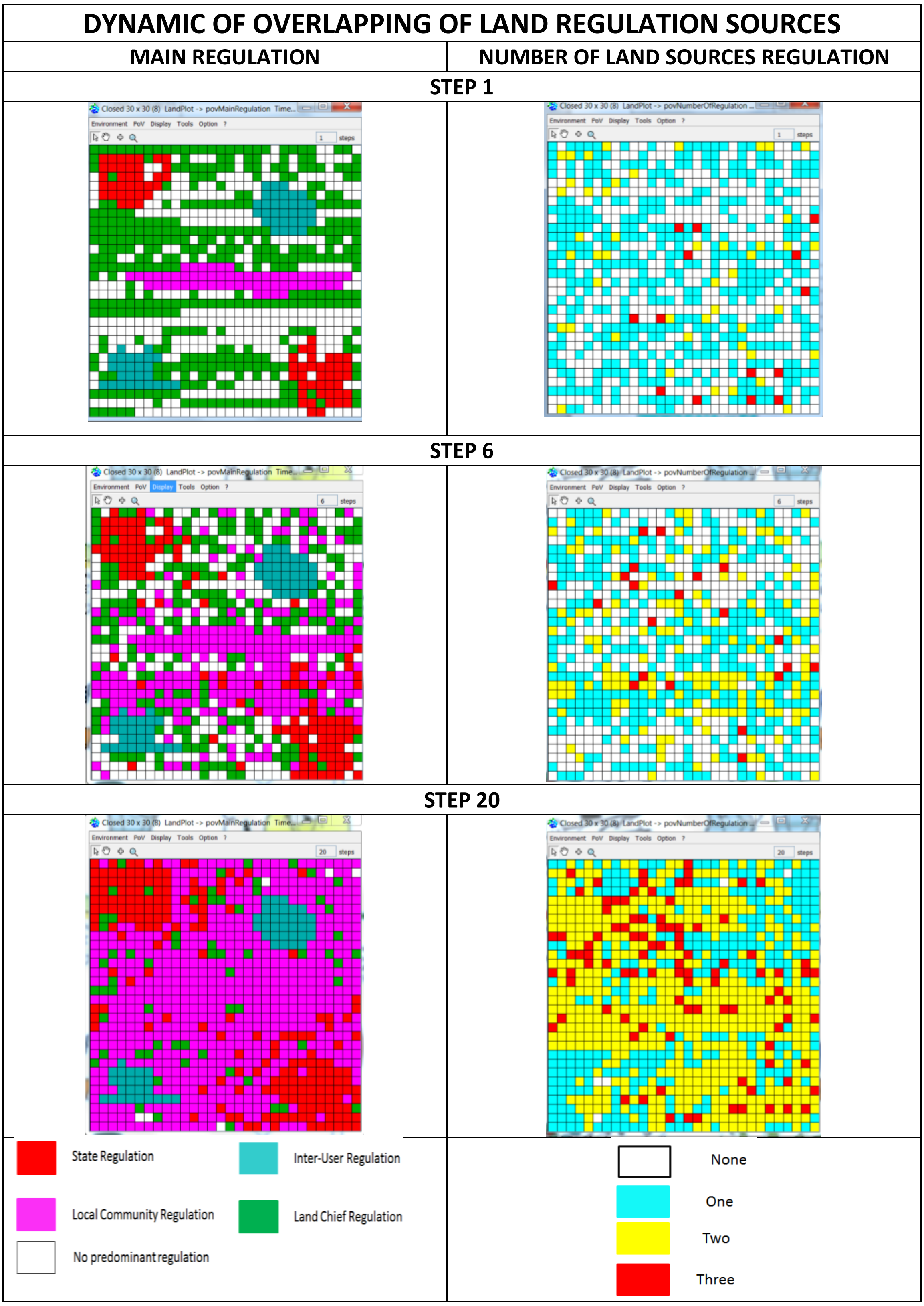


Figure 22: illustration of a pluralism of land regulation of the land plots of the agent-based model environment

4. MODEL VERIFICATION AND VALIDATION

Verification of a model means "getting the model right" (Parker et al. 2003). Model validation is "getting the right model" (Parker et al. 2003), meaning that the correct abstract model was chosen and accurately represents real-world trends and patterns. Verification and validation of ABMs have been the focus of much attention (Robinson et al. 2007, Filatova et al. 2013).

The agent-based model was verified using complementary verification procedures: a code review by another agent-based modeler and a set of stress tests to monitor the behavior of the model in extreme situations. We also implemented unit tests for each sub-model that run parts of the model in a controlled way and then ran the model with very few agents in order to examine the results closely (e.g. according to the life history of each specific agent). The parametrization of the agent-based model as it stands is based on an indirect proportional calibration (abstract units, real ratios). We used our empirical data to run large numbers of calibrations with various model parameters and we compared our model outputs with empirical data. We finally chose the combination of model parameters which replicated the empirical data best (Schwarz and Ernst 2009) and sufficiently well reproduced patterns actually observed in in the field (Grimm 2006, 2010).

There are a number of ABM validation approaches (Bousquet et al. 2003, Castella et al. 2005, Janssen and Ostrom 2006, Grimm 2006, 2010, Schwarz and Ernst 2009). Our validation aimed to ensure that the fundamental structural and behavioral components in the agent-based model captured the main aspects of the actual stakeholder-oriented pluralism of land regulation. We thus ran a set of consistency checks to validate the default situation we sought to represent. The agent-based model involves a lot of parameters, with a large proportion of randomization in the initial choices of value (but the different potential values are all known). The default situation we seek to represent is a pluralistic Sahelian land regulation pattern, so the part of plurality and uncertainty (illustrate by the use of randomization) is essential. The consistency tests consisted on initially set parameters which were normally randomly chosen

As a reminder, this default situation represents a pluralist Sahelian environment composed of different natural environments (i.e. land types) linked to a high variability and uncertainty regarding natural resources evolution and availability (through random annual rainfall). This environment is divided in land territories managed by different water and land chief regulator agents according to their own logic of action (prioritizing economic, social or environmental objectives). User agents have specific and diversified perception of land tenure security, composed by a diversified level of information on the resources surrounding them and on the source(s) of regulation managing it (through their specific value of their attribute "perception of resource regulation") and by a diversified level of investment security (through their specific value of their attribute "perception of access right duration").

We realized most of the tests at the space scale of the choice of INIT B (a land plot area is equal to 50 hectares), where user agents represent villages (as grouping of several families) evolving on a space equivalent to a set of local communities. I chose to work on this space scale (1) because it is the first one on which I developed the conceptual agent-based model, it is therefore the more accomplished one, and (2) because this scale propose an intermediary analysis window of the pluralism of land regulation, between a more local one (at the scale of few villages) and a more general one (at the scale of a large region).

Simulations for the tests are based on a 10 years temporality, equivalent to 20 steps (one step = one dry/rainy cultural season) for each simulation. Each consistency test simulation has been repeated 20 times. Each graphic of the results chooses the evolution of the different observed indicators for each repetition.

(0) Scenario by default : simulation of a traditional pluralism of land regulation (**left column** of the attached figures 3 to 6)

This reference simulation is a twenty repetition of the default pluralist land regulation situation, where land access are delivered by land chief agents (without any introduction in the simulation of another source of land regulation) according to a plurality of logics of action. The characteristics of the water and resource access rights delivered (nature, price, duration, periodicity, quantity of water of hectares delivered etc.) depend on the regulator logic. The rainfall and natural resource dynamics are subject to the uncertainty and variability of a Sahelian environmental context. The observed results show that on average between half and two third of the user agents have ongoing resource access rights over time (3.1 to 6.1) and that these resource access rights concern between one and two third of the land plots (3.2 to 6.2). According to the quality of annual rainfall, and to the alternation of rainy and dry seasons the number of user agents benefiting from water access rights strongly varies[2] (3.3 to 6.3). The number of user agents realizing rural activities over time also strongly varies according to the alternation of rainy and dry season, because in the dry seasons activities depends on water access (no water access rights, no possibility of realizing an activity for the user agents) (3.4 to 6.4). This pluralist traditional land regulation management leads to an overall good environmental state of water (3.5 to 6.5) and natural resources (3.6 to 6.6), which tend to stand or increase over time. All in all, the randomization of regulators' logics of action choices and of rainfall dynamic seems to have a significant impact on several indicators, according to the disparity of probe evolutions within the repetitions.

(1) Scenario of the consistency Test One: only good annual rainfall (see attached figure 1)

For this first consistency test, we only changed the rainfall dynamic parametrized by default with the respective probabilities of occurrence: good rainfall (1/6), medium rainfall (1/3), bad rainfall (1/2) to only good rainfall at each step of rainy season (one in two step). The idea was to test if the removal of Sahelian high uncertainty and variability regarding rainfall and natural resource replenishment has a significant impact on the evolution of natural resources. If we compare the results of this consistency test to the ones of the default situation, the observed indicators confirm indeed that with only good annual rainfall, water and natural resources are consequently more abundant.

(2) Scenario of the consistency Test Two: only seasonal resource access rights distributed by land regulators (see attached figure 2)

Land regulators have by default the possibility to decide, according to their logic of action, of the duration of each resource access right they distribute to the users (from seasonal access rights to access rights available for several years). For this consistency test, we set this duration to only seasonal resource access rights (available only for the season or the step). This second consistency test has been developed to test the meaning of different indicators, and to insist on the fact that a single indicator often shows only part of the information and it remains an interesting exercise to cross this first information with other indicator evolutions, to have a better understanding of what is happening overall in the simulation. Here, if we compare the results of the consistency test with the ones of the default situation, some of the observed results pointed out that users have no access rights in their

[2] The strong variation rainy/dry season is illustrated by the saw-tooth reading of the probes

portfolio neither have a use of a land plot anymore (2.1 and 2.2). But if we look another indicator showing the proportion of users that realize rural activities (for which they need to have resource access rights) at each step, this indicator evolves during the simulation, illustrating the weaker but existing seasonal resource access right interactions (2.3). Interactions between users and regulators on one hand, and between users and the land plots on the other hand are not visible in time because they last only for one season and are happening quietly within the step, but this consistency test shows that they exist anyway.

(3) Consistency tests on fixation of water and land regulator logic of action

The following four consistency tests have been developed in order to test the effect of the plurality of land and water regulators logics of action. In the default situation, regulator agents have indeed initially a random choice between four logics of action to allocate land and water access rights: economic, social, environmental pro conservation and environmental pro restoration. For each of the four consistency tests, this choice of logic of action has been fixed, and for some test linked to other "extreme" situations (i.e. modifications of other parameters). The same set of indicators is observed for each of these four consistency tests of regulators logics of action.

(4) Scenario of the consistency Test Three: only social priority logics of action for water and land regulators (see attached figure 3)

For this consistency test, we fixed all the water and land regulators with logics of action prioritizing social objectives. It means that water and land access are free in term of cost, and that regulators care to give equal resource and water access rights to each of the requesting users. If we compare the results of the consistency test with the ones of the default situation, results show that consequently to this "free fare access", almost every user agent has a water and a land access right (3.1), and the hole environment is open to users (i.e. almost each land plot has at least one user with a resource access right allowing him to farm it) (3.2). But because regulator agents do not monitor the environmental state of water sources and natural resources before allowing access to it, these resources are totally consumed at each rainy season (3.5 and 3.6), meaning that there is not more water or natural resource available at each dry season for the users to realize their rural activities at this period (3.3 and 3.4).

(5) Scenario of the consistency Test Four: only environmental conservation priority logics of action for water and land regulators on an environment only composed of fertile lowlands (see attached figure 4)

For this consistency test, we fixed all the water and land regulators with logics of action prioritizing conservation environmental objectives. It means that all regulators will estimate the natural state of their resource (water, fodder, fertility, NTFP) before allowing access on the land plot or the water source, and **above** a certain threshold they will close this access in order to optimize the environmental durability of the resource. We also fixed the environment which by default is composed of 1/3 of fertile lowlands, 1/3 of intermediary sandy soils and 1/3 of degraded soils, to only fertile lowland land plots. This extreme situation has been developed in order to test the reactivity of enviro-conservationist regulators when all the natural resources are in great environmental state (and are therefore qualify to be protected from use by the regulators, to optimize their conservation). If we compare the results of the consistency test with the ones of the default situation, results show that from the beginning of the simulation, the threshold of natural resources is exceeded for land regulators, and they directly close the access to their land plots in order to create protected natural reserves. Therefore, even if some of the users still succeeding in obtaining water access rights (4.3), no users have resource access rights (4.1), no one realize any rural activities (4.4) and none of the land plots are under user farming (4.2). Water and natural resources are consequently abundant (4.5 and 4.6).

(6) Scenario of the consistency Test Five: only environmental restoration priority logics of action for water and land regulators on an environment only composed of degraded soils (see attached figure 5)

For this consistency test, we fixed all the water and land regulators with logics of action prioritizing restoration environmental objectives. It means that all regulators will estimate the natural state of their resource (water, fodder, fertility, NTFP) before allowing access on the land plot or the water source, and **under** a certain threshold they will close this access in order to allowing the replenishment of the different resources. We also fixed the environment which by default is composed of 1/3 of fertile lowlands, 1/3 of intermediary sandy soils and 1/3 of degraded soils, to only degraded soil land plots. This extreme situation has been developed in order to test the reactivity of environmental regulators with restoration logics when all the natural resources are in poor environmental state (and are therefore qualify to be protected from use by the regulators, to optimize their replenishment). If we compare the results of the consistency test with the ones of the default situation, results show that the number of user agents with resource access rights on their portfolio (5.1), and the number of land plots for which user agents possess ongoing access rights (5.2) depend more of the rainfall dynamic and the succession of dry and rainy seasons. The same number of users realizes activities over time (5.4), but on a lower number of land plots. The environmental water regulation is more severe than the land one, and at best only one third of the user agents receive water access rights at the end of the simulation (5.3). At last, the environment being only composed of degraded soils, the environmental state of fodder resources is lower than for the default situation (5.6) even if an environmental regulation is established.

(3.1) Scenario of the consistency Test Six: only economic priority logics of action for water and land regulators, with only high water and land access prices (see attached figure 6)

For this consistency test, we fixed all the water and land regulators with logics of action prioritizing economic objectives. Water and land access prices are fixed to their higher unit values and all regulators choose to give resource and water access rights in priority to the requesting users with the higher capital. Results show that as same as for the consistency test with the regulators' logics of action fixed on social priority objectives, the non-consideration of the environmental state of natural resources before allowing access to it leads to a situation where almost every user agents have ongoing resource access rights (6.1) on the totally of the environment (6.2) (all the land plots have user agents with ongoing access rights to it). But contrary to the social priority objectives, user agents have to pay this time in order to access to the right to (invest in the) use of a land plot, and few of them are able to afford this land price (the same reasoning is applying to water access rights). This leads to a situation were less than half of the users realize activities during the raining season (6.4) (against the totally of the users for the social priority consistency test, and the three-quarters for the default situation).

(7) General review of the consistency tests

The pluralist default situation seems to create a form of balance between human and environmental interactions (social actions vs environmental sustainability). The balance is troubled each time we reduce the plurality and the random aspect of the significant parameters of the agent-based model. Based on this pluralist default situation, a lot of simulation scenarios are possible according to the question or the areas each potential user of the agent-based model wants to explore.

5. EXPLORATION OF NEW LAND REGULATION SOURCE(S) SIMULATION SCENARIOS

As explained before, land use policies have accentuated over time this already existing complexity. Indeed, rather than abandoning their practices, local populations have added the land tenure policies set up successively to their pre-existing sources of regulation. The aim of the developed scenarios of simulation was to explore these additions of new land regulations to the complexity existing by default, with regards to the ways users seems to perceive these changes, and take them (or not) into account in their logics of mobilization of a pluralism of land regulations.

As a reminder, a user at least partially base his perception of land tenure security on the ways other users already exploiting the spaces that interest him have obtained their own land access rights. The recognition by the other users, because this recognition assures him a non-contesting of his resource access right(s). This prevalence of a land regulation source is therefore defined as the source of regulation which is the most mobilized by the users of the area already exploiting the concerned natural resource. Changes in users'practices of mobilization of land regulations will therefore pass through changes in their perceptions of land tenure security linked to these prevalences of land regulation sources.

Besides, changes in land regulation can be introduced through a diversity of **intensities** (as the proportion of users mobilizing this new land regulation source on a same area) and **configurations** (as the spatial distribution of the users mobilizing the new land regulation source). This leads to a diversity of landscape composition evolutions at a general scale, according to the introduced changes. For example, a new development project can bring changes in land regulation on one or several contigous areas (the project works with all the users of a village, of a local community, of a hydro-agricultural area…). A new land use policy will however concern all the users of the country, oftenly on a volontary basis (users have to launch the process of converting and formalizing their land rights).

According to the intensity and the configuration of the introduced change, its nature, the pre-existing perceptions of land tenure security that users of the area(s) concerned by the land regulation change have or not, the expression of this stakeholder-oriented pluralism of regulation will vary. The scenarios of simulation particularly aim to explore the concept of perception thresholds, above which changes are observed in users' practices of mobilisation of land regulation sources, but below which no matter the nature of the introduced change (for example, a new land use policy), it does not seem to be perceived, or in any case considered by Sahelian users.

In order to do so, I chose to explore the diffusion of (a) new source(s) of land regulation, according to (1) the diversity of ways it can be introduced in the pluralist default situation of the agent-based model, (2) in relation with the diversity of users 'perceptions, participating to the dissemination within the users' practices of these new sources of regulation, above certain thresholds.

These simulation scenarios can be explore in the agent-based model at the space scale of a village territory (INIT A), a set of local communities (INIT B) or a region (INIT C). I chose to realize the simulations at the scale of INIT B, to keep the idea of an intermediary analysis window of the pluralism of land regulation, between a more local one (at the scale of few villages) and a more general one (at the scale of a large region).

i. **First set of simulation scenarios: to explore the dissemination of new land regulation source(s) according to its introduction pattern**

In addition to the initial/by default traditional land chief regulations, the agent-based model considers 3 possible types of regulator agents linked to 3 sources/systems of regulation existing within the pluralism of land regulations for securing access to resources:

- the local community agents, representing the decentralization policy (several new agents created),
- the state agent, central as regionalized (a single new agent created),
- the inter-users regulations (implemented directly by the user agents, no new agents created).

For this set of simulation scenarios, I choose to work with the local community agents and the state agent, because they represent two different sources of external changes in the traditional by default land regulation. The state agent represent a single “top-down” regulator with its unique logic of action (which he randomly initially chooses) for allocating resource access rights on his land plots (representing the whole environment) while several local community agents are created, and each local community regulator agent initially choose its own logic of action to manage the resources of his decentralized territory (representing a portion of the whole environment).

Perceptions of user agents are here plural and specific to each user agent, randomly chosen (between 1 and 15) at the initialization of the model. The environment of the agent-based model is composed of 900 land plots, each land plot representing a 50 hectares area, for a total area of 45 000 hectares. A new land regulation source can appear in this environment through:

- a certain intensity: as the proportion of users mobilizing this new land regulation source on a same land plot. According to the nature of the new land regulation, the initial value of intensity on a land plot is introduced through the attributes: localCommunityUpdateValue and stateUpdateValue of each land plot;
- a certain configuration: as the gathering of (1) the number of land plots concerned by this new land regulation source with (2) the distribution of these land plots (randomly spread within the whole environment, or contiguous on a certain area of the environment (for example: a village, a local community…). These variables are explored through the attributes: numberOfStateUpdate and numberOfLocalCommunityUpdate (for the number of land plots concerned by the new land regulation) and through the attribute choiceOfInitRegulation defining if the introduction pattern is contigous-localized or randomly spread within the environment of the agent-based model.

We developed two series of simulation scenarios (see Table 16): one with a fixed intensity and a variable configuration, and one with a fixed configuration and a variable intensity. For each of these series, the new land regulation is introduced either by the State or by the local community agents. The idea behind this separate introduction is to test if the diffusion of a new land regulation is different depending on whether it is introduced through one central general regulator or through several decentralized local regulators.

Simulations for the scenarios are also based on a 10 years temporality, equivalent to 20 steps (one step = one dry/rainy cultural season) for each simulation. Each scenario has been repeated 10 times. Each graphic of the attached figures A, B, C and C presenting the results chooses the average of the evolution of the different observed indicators for each repetition (i.e. one probe represent an average of 10 simulations). The calibration of the scenarios (the fact that we simulate during 20 steps, the value interval, the fixed value to the number 20 etc.) results from an experimental stage of simulation conducted to build the scenarios and consequently to test the responses of the agent-based model.

Table 16: overview table of our set of simulation scenarios

NATURE OF THE NEW LAND REGULATION SOURCE	CONFIGURATION OF THE CHANGE		INTENSITY OF THE CHANGE	SCENARIO NUMBER	SYNOPSIS OF THE SCENARIO	FIGURE
	DISTRIBUTION	NUMBER OF LAND PLOTS				
STATE	RANDOMLY SPREAD	Variable 1-100	Fixed, 20	1	A new land policy is conceived and implemented by the State. The new "fictive" users mobilizing the State for accessing land resources are disseminated within the whole country, and local initiatives of land interaction with the State emerge from an increasing number of local areas in the country, with a constant intensity of new "fictive" users mobilizing the State on each local area.	FIGURE A left column
		Fixed 20	Variable 1-100	2	A new land policy is conceived and implemented by the State. The new "fictive" users mobilizing the State for accessing land resources are disseminated within the whole country, on specific constant local areas. The intensity of "fictive" users mobilizing the State regulator on each of these constant local areas is increasing from one to one hundred users.	FIGURE B left column
	CONTIGUOUS-LOCALIZED	Variable 1-100	Fixed, 20	3	A new land policy is conceived and implemented by the State. The new "fictive" users mobilizing the State for accessing land resources are neighbors who share a common contiguous spatial area of the environment. This contiguous spatial area constitutes an increasing portion of the whole environment. The intensity of "fictive" users mobilizing the State regulator on each land plot of the contiguous area is constant.	FIGURE C left column
		Fixed 20	Variable 1-100	4	A new land policy is conceived and implemented by the State. The new "fictive" users mobilizing the State agent for accessing land resources are neighbors who share a common contiguous spatial area of the environment, of a constant size of 1000 hectares. The intensity of "fictive" users mobilizing the State regulator on each of the land plots of this contiguous area is increasing from one to one hundred users.	FIGURE D left column

LOCAL COMMUNITY	RANDOMLY SPREAD	Variable 1-100	Fixed, 20	5	A new land policy is conceived by the State but implemented by the local community regulators through a decentralization policy. The new "fictive" users mobilizing the local community regulators for accessing land resources are disseminated within the whole country, and initiatives of land interaction with the local communities emerge from an increasing number of local areas in the country, with a constant intensity of new "fictive" users mobilizing the local community of each local area.	FIGURE A Right column
		Fixed 20	Variable 1-100	6	A new land policy is conceived by the State but implemented by the local community regulators through a decentralization policy. The new "fictive" users mobilizing the local community regulators for accessing land resources are disseminated within the whole country, on specific constant local areas. The intensity of "fictive" users mobilizing the local community regulator of each of these constant local areas is increasing from one to one hundred users.	FIGURE B Right column
	CONTIGUOUS-LOCALIZED	Variable 1-100	Fixed, 20	7	A new land policy is conceived by the State but implemented by the local community regulators through a decentralization policy. The new "fictive" users mobilizing the local community regulators for accessing land resources are neighbors who share a common contiguous spatial area of the environment. This contiguous spatial area constitutes an increasing portion of the whole environment. The intensity of "fictive" users mobilizing the local community regulator of each land plot of the contiguous area is constant.	FIGURE C Right column
		Fixed 20	Variable 1-100	8	A new land policy is conceived by the State but implemented by the local community regulators through a decentralization policy. The new "fictive" users mobilizing the local community regulators for accessing land resources are neighbors who share a common contiguous spatial area of the environment, of a constant size of 1000 hectares. The intensity of "fictive" users mobilizing the local community regulator of each of the land plots of this contiguous area is increasing from one to one hundred users.	FIGURE D Right column

Choice of indicators

For this set of scenario simulations, we chose to explore the diffusion of a new land regulation source according to its introduction pattern through the evolution of users activities realized with resource access rights obtained by these different sources.

We therefore followed the evolution of the indicators:

- stateLevel: recording the number of activities realized by user agents over time through resource access rights delivered by the state agent;
- localCommunityLevel: recording the number of activities realized by user agents over time through resource access rights delivered by local communities agents;
- landChiefLevel: recording the number of activities realized by user agents through resource access rights delivered by land chief agents.

Results analysis

Results tend to show that ***no matter the characteristics of the new land regulation introduction pattern, a threshold, above which user agents mainly mobilize the new source for accessing resources (but under which this mobilization stays minimal), exists***. As the panels 1 of the attached figures A to D show, the value of this threshold varies according to the new land regulation introduction pattern but stays concentrated around the value interval: [20-40], no matter the simulation fixed the intensity or the configuration of the new land regulation introduced. Each probe of the graphic shows the evolution of the number of users (on a total of 1000) mobilizing the State (left graphic) or the local Communities (right graphic) for the realization of their activities at each season over time. The strong variation rainy/dry season illustrated by the saw-tooth reading of the probes still represents the high variability of water and natural resource availability from one season to another, affecting the number of water and resource access rights delivered and so on the number of users able to realize an activity.

Besides, for the same values of intensity and configuration of introduction pattern, ***the new land regulation source observes a more widespread diffusion when it is initially randomly spread within the entire environment than when it is introduced only on a contiguous localized area***. Panels 1 of the Figures A and B show that between 800 and 1000 users mobilize the new land regulation source above the threshold of perception whereas it concerns only 350 to 600 users on the panels 1 of the Figures C and D. And these proportions are rapidly achieved when the introduction pattern is randomly spread whereas probes are slowly increasing to reach their final level when the introduction pattern is contiguously localized.

This last statement is confirmed by the impact of the new land regulation source on the initial traditional land chief regulation. ***When the introduction of the new source is randomly spread, results show a threshold above which the land chief regulation nearly disappears while when this introduction is contiguously localized it has almost no impact on the mobilization of land chief regulation by the users***. Indeed, above a threshold of 40-50 for the value of the variable parameter (intensity of number of land plots), panels 2 of the figures A and B show that the mobilization of the initial traditional land chief regulation sources is reduced to a minimum whereas such a threshold does not exist on the panels 2 of the Figures C and D where around 700 users still mainly mobilize the traditional land regulation at the end of the simulation.

Moreover ***the plurality of local community regulators' logics of action for managing their respective territories seems to favor a longer time a pluralism of land regulation whereas the expression of the unique logic of action of a State managing by himself the whole environment seems to encourage a***

more exclusive State land regulation (once user agents decide to mobilize it). The overall comparison of the left and right columns of the figures A to D shows indeed that the final levels of the probes are reached more rapidly when only the State regulation is introduced, and that the values of these final levels are higher.

Finally, the fact of introducing the new land regulation source with a variable intensity (as the proportion of users mobilizing this new land regulation source on a same area) (Figure B and D) or a variable configuration (Figure A and C) (as the spatial distribution of the users mobilizing the new land regulation source) does not seem to influence the results, the trend of the observed probes are broadly similar.

All of these results are linked to the fact that users have specific and diversify perceptions on the resources that surrondind them and on the sources of land regulation that predominantly managing it. A secund set of simulation scenarios has been developped to test the significance of this particular parameter on the potential of diffusion of a new land regulation source, and on the pluralism of regulation observed overall.

ii. Secund set of simulation scenarios: to explore the dissemination of new land regulation source(s) according to users 'perceptions

For this set of simulation scenarios, we fixed the values of intensity and configuration of the new land regulation source introduction patterns. Each new regulation is introduced in the agent-based model with an intensity (per land plot) of 30 fictive new users, on a 20 land plots distribution. This calibration result from the first set of scenario simulations (see above) on the introduction pattern analysis.

On this basis, as same as for the first set of scenarios, we developed two simulation scenarios, one with a randomly spread distribution of these new land regulation sources, and one with a contiguously localized distribution. This time, the two potential new land regulation sources (state and local community regulation) are introduced simultaneously.

As a reminder, user agents have an attribute "perception of resource regulation", by default specific to each user agent (varying from 1 up to 15 for the INIT B). This reflects the idea that the level of information that land actors possess about land regulations strongly vary from one user to another, some of them have a perception that only extend on their village, or their land territory whereas others will know what is happening in the all country (i.e. the total environment of the agent-based model). For this set of simulation scenarios, the diversity of users 'perceptions is replaced by a progressively increasing homogeneous perceptions, starting from 1 (all user agents have their attribute value equal to 1) and ending at 30 (all user agents have their attribute value equal to 30) at the end of the simulation.

<u>Choice of indicators</u>

For this set of scenario simulations, we also chose to explore the expression of a pluralism of land regulation sources through two series of indicators the evolution of users activities realized with resource access rights obtained by these different sources, as same as for the first set of scenarios: stateLevel, localCommunityLevel, landChiefLevel, otherUserLevel.

<u>Results analysis</u>

Some of the results of the first set of simulation scenarios already showed that the plurality of local community regulators logics of action for managing their respective territories seems to favor a longer time a pluralism of land regulation. ***The current results specify that the pluralism of land regulation is also partially linked to the diversity of users 'perceptions/information asymmetry. For the same values of intensity and configuration of introduction pattern, this pluralism of land regulation sources express itself longer when the new sources of land regulation are introduced only contiguous localized areas.***

Indeed, when the new sources of land regulation appear randomly spread within the environment (Figure G), results show that a form of pluralism is possible at the beginning of the simulation, but after a few steps, especially if users 'perceptions are above 10-15, the State become the predominant source of regulation for all user agents (G.4), except for some simulations where it is the Local Community regulation that predominates (G.2), but it is strictly one or the other, no pluralism is possible). For the last two levels of perception (29-30), all the user agents know all the environment in terms of natural resources and their regulations, and it seems to induce a total incapacity for the new sources of regulation to appear in users 'practices, they mobilize only the land chief agents (G.7 and G.8) because their general initial prevalence at the scale of the whole environment is stronger than the new regulation sources intensity of introduction (30 intensity/ 20 distribution). This unique mobilization of land chief agents also seems to reduce the number of users who actually access to resources, because all users ask to the same land chiefs (because they want to reach the same quality of resources, and so on the same land plots…)).

When the new sources of land regulation are introduced on contiguous localized areas (Figure H), the pluralism is allowed until the end of the simulation, and the local community sources (H.1 and H.2) seems to disseminate and stabilize more effectively where the State regulation tend to disappear after a few steps (H.3 and H.4). No new sources of regulation are maintained in users 'practices before the latter reach a level of perception equal minimum to 14-15. Between a 16-26 level of perception, local communities are the predominant source of regulation for all the user agents (H.2), and the land chief regulation reach its lower level (H.8), but this level increase again when users 'perceptions are high (29-30) and finish at the end of the simulation at a higher level than when the new sources appear randomly.

All these scenarios has been simulated to the space scale of INIT B, but the agent-based model allows the possibility of choosing two complementary scales of analysis in order to complete the exploration of a pluralism of land regulation (see Box 1).

Box 1: complementary set of simulations in order to explore the diffusion of new land regulation source(s) according to the space scale of the agent-based model

For this set of simulation scenarios, we fixed the perceptions of user agents, as plural and specific to each user agent, randomly chosen (between 1 and 15) at the initialization of the model, and we also fixed the introduction pattern of the new land regulation source. Each new regulation is introduced in the agent-based model with an intensity (per land plot) of 30 and a 30 land plots distribution. We then developed two simulation scenarios, one with only the State new regulation introduced (see attached Figure E) and one with only the Local Community new regulation introduced (see attached Figure E) (and the new land regulation sources still appear randomly or in contiguous-localized areas of the environment).

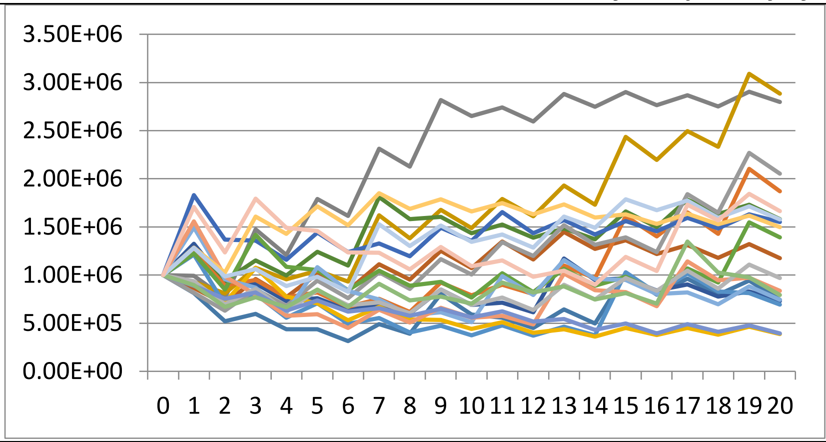
Result analysis

For the same values of intensity and configuration of new regulation introduction pattern on the three space scales, the diffusion of the new source is general on the INIT A (land plot size = 1 ha), no matter the characteristics of the introduction pattern (randomly spread of contiguously localized, through the State or the local community agents). While these characteristics play a role on the new land regulation source diffusion at the scales of INIT B (land plot size = 50 ha) and INIT C (land plot size = 1000 ha).

Indeed, when the new source appears randomly in the environment, the diffusion mainly becomes total whereas when the new regulation source is localized it only concerned at the most one fifth of the users' rural activities. The impact of these new sources of land regulation on the initial traditional regulation through land chief agents is significant at the scale of INIT A (the level of users 'rural activities that mobilize land chiefs for accessing resources tend to be reduced to a minimum). At the scale B and C, it is only significant if the new source is randomly introduced.

6. ATTACHED FIGURES

ATTACHED FIGURE 1

<table>
<tr><td colspan="3">Scenario of consistency Test One: only good annual rainfall</td></tr>
<tr><td>Cormas Indicator</td><td>DEFAULT SITUATION</td><td>STRESS TEST SITUATION</td></tr>
<tr><td rowspan="2">wellWater Quantity</td><td colspan="2">1.1 Evolution of the quantity of water available in the wells over time</td></tr>
<tr><td>


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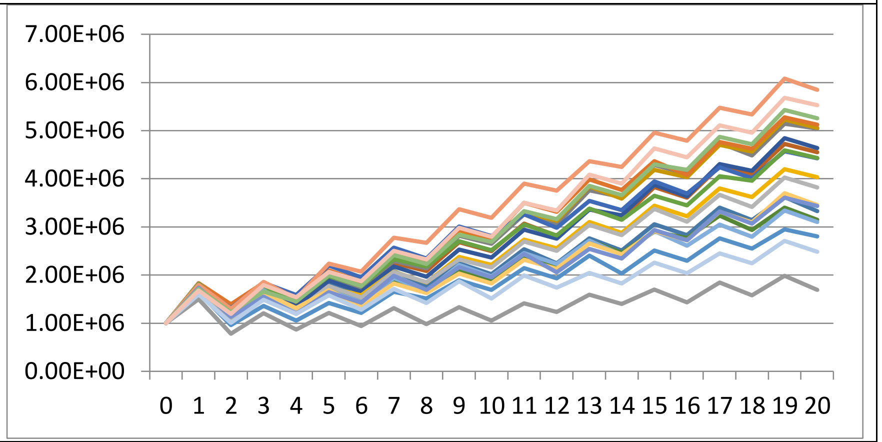

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<tr><td rowspan="2">drillingWater Quantity</td><td colspan="2">1.2 Evolution of the quantity of water available in the drillings over time</td></tr>
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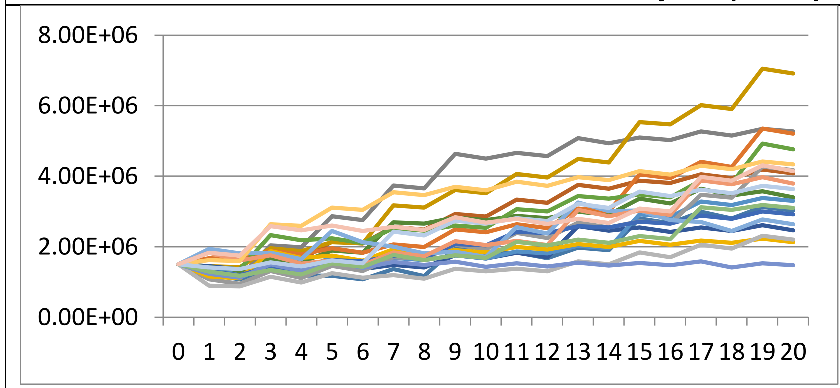

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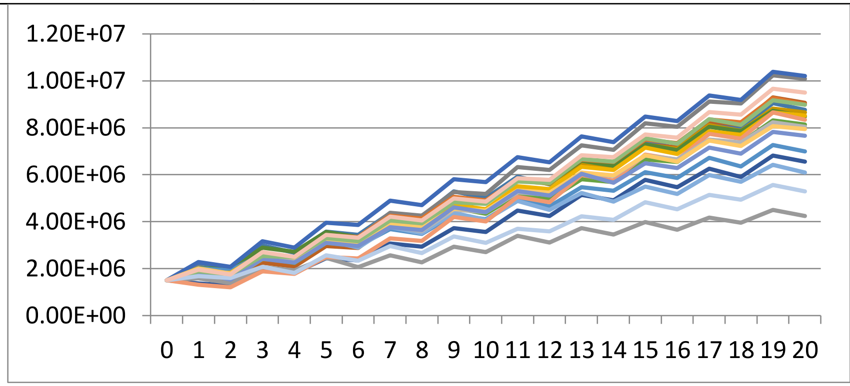

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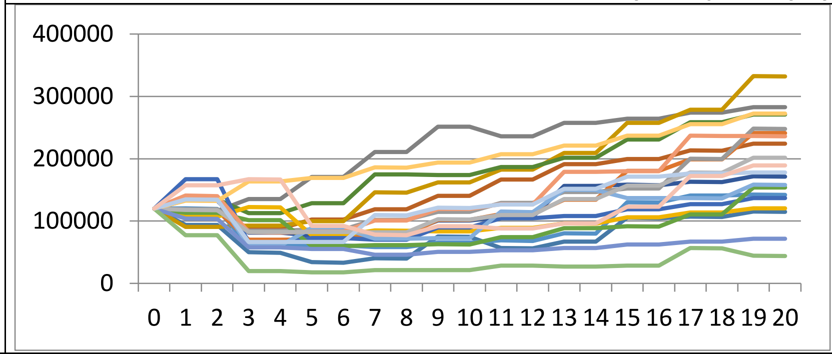
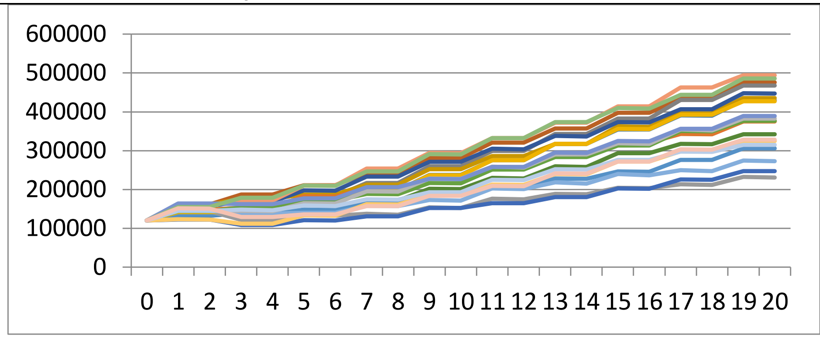
landPlotFertility

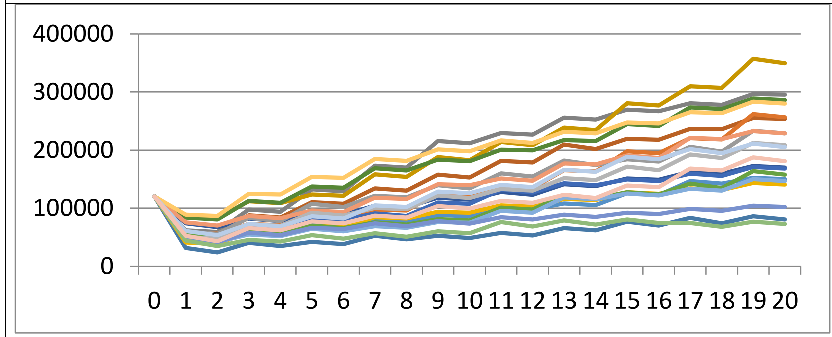
1.3 Evolution of the quantity of fertility available on the land plots over time

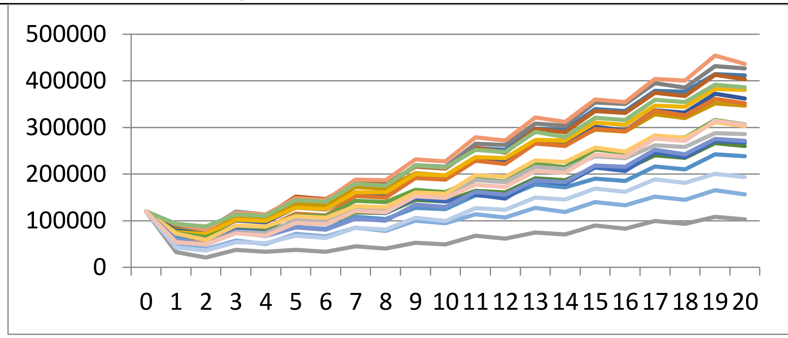




landPlotFodder

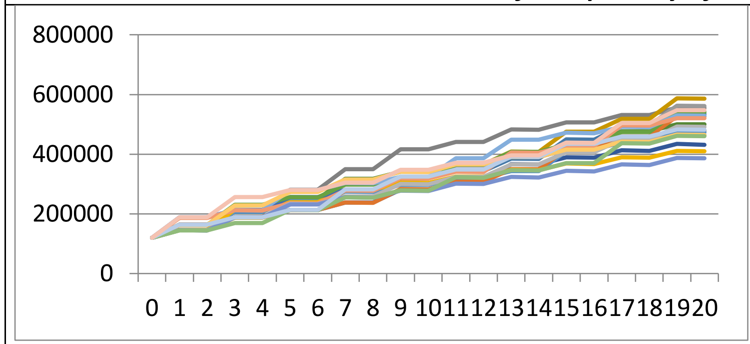
1.4 Evolution of the quantity of fodder available on the land plots over time

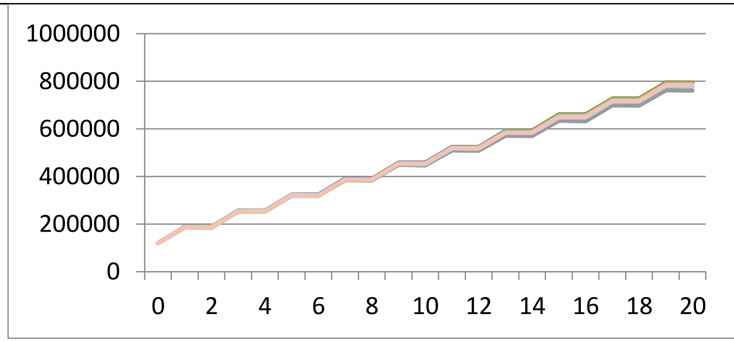




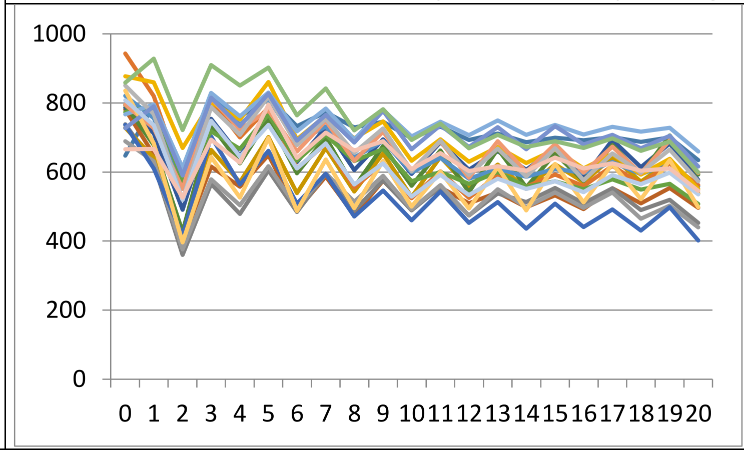
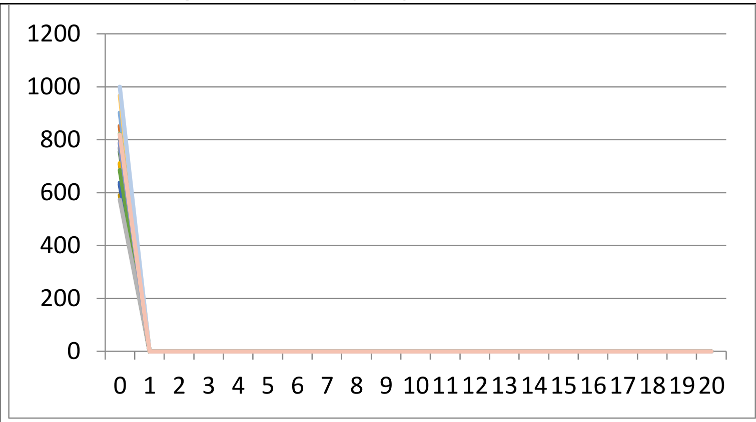
landPlotNTFP

1.5 Evolution of the quantity of non-timber forest products available on the land plots over time





ATTACHED FIGURE 2

<table>
<tr><td colspan="3">Scenario of consistency Test Two: only seasonal resource access rights distributed by land regulators</td></tr>
<tr><td>Cormas indicator</td><td>DEFAULT SITUATION</td><td>STRESS TEST SITUATION</td></tr>
<tr><td rowspan="2">numberOfUsersWith ResourceAccessRights</td><td colspan="2">2.1 Evolution of the number of user agents with resource access right(s) in their portfolio over time</td></tr>
<tr><td>
</td><td>
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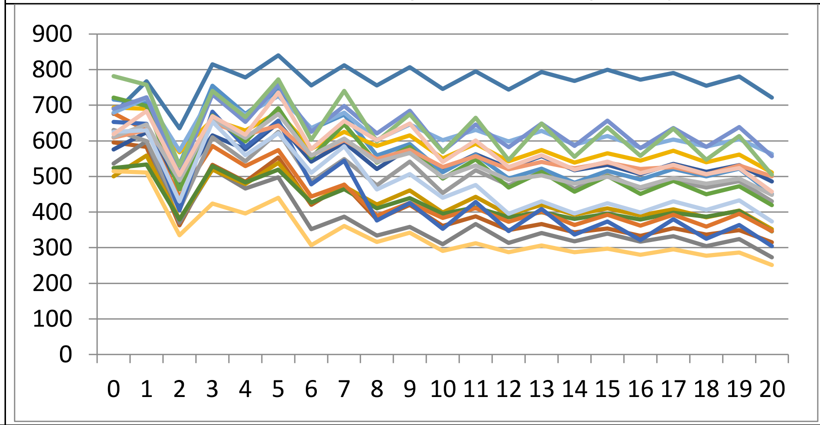
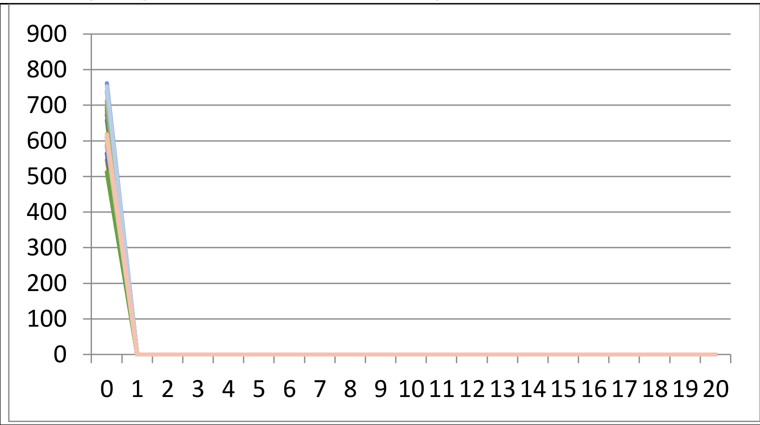
<tr><td rowspan="2">numberOfLand PlotUsers</td><td colspan="2">2.2 Evolution of the number of land plots concerned with ongoing user resource access rights over time</td></tr>
<tr><td>
</td><td>
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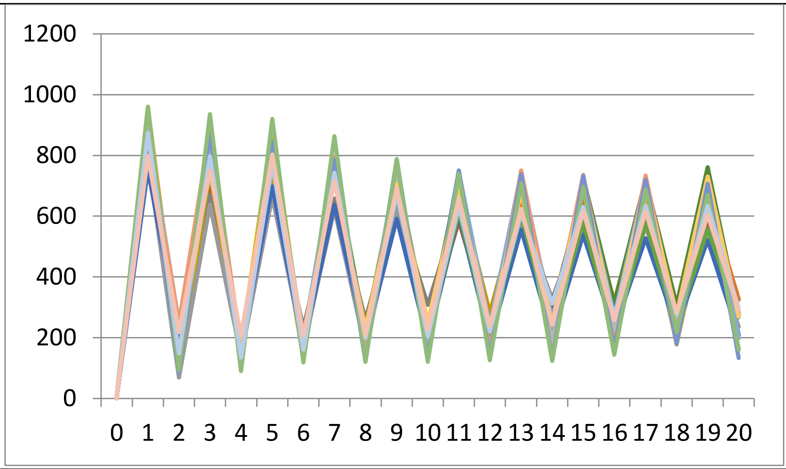
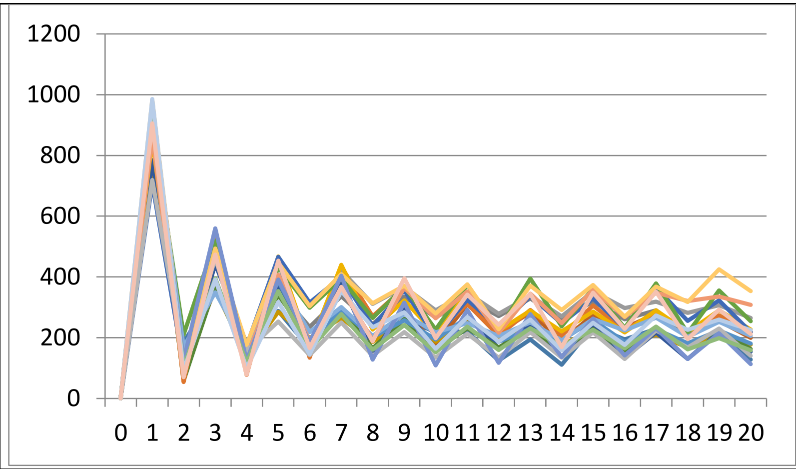
<tr><td></td><td colspan="2">2.3 Evolution of the number of user agents realizing activities over time</td></tr>
</table>

numberOfUsers WithActivities		

ATTACHED FIGURE 3

Scenario of consistency Test Three: only social priority logics of action for water and land regulators		
Cormas Indicator	**DEFAULT SITUATION**	**STRESS TEST SITUATION**
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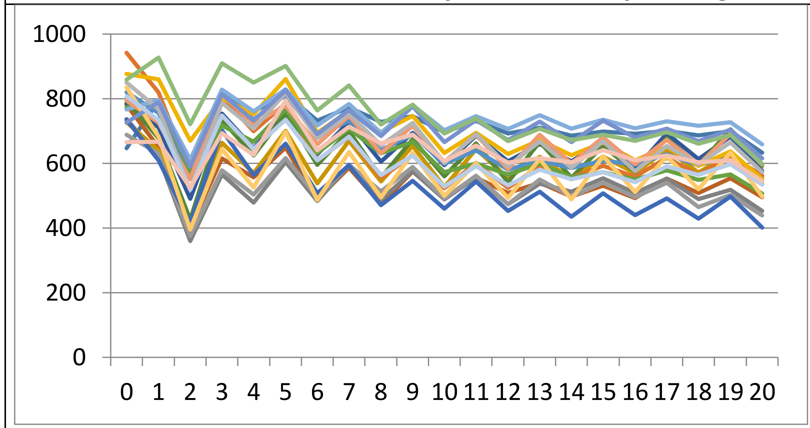
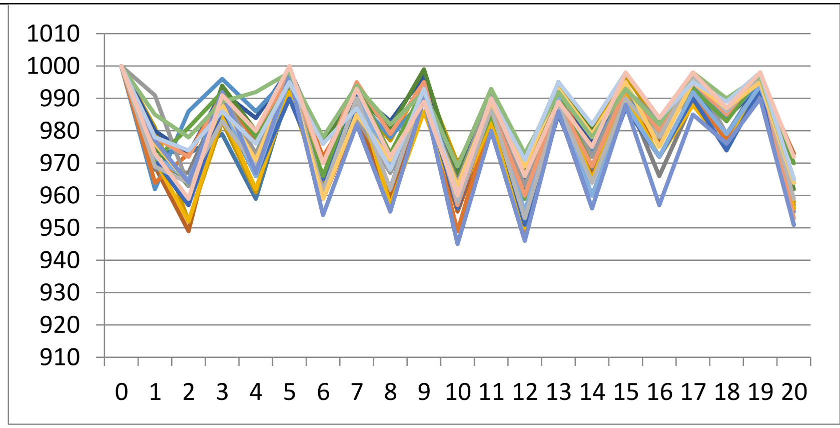
numberOfUsersWith ResourceAccessRights		
	3.2 Evolution of the number of land plots concerned with ongoing user resource access rights over time	

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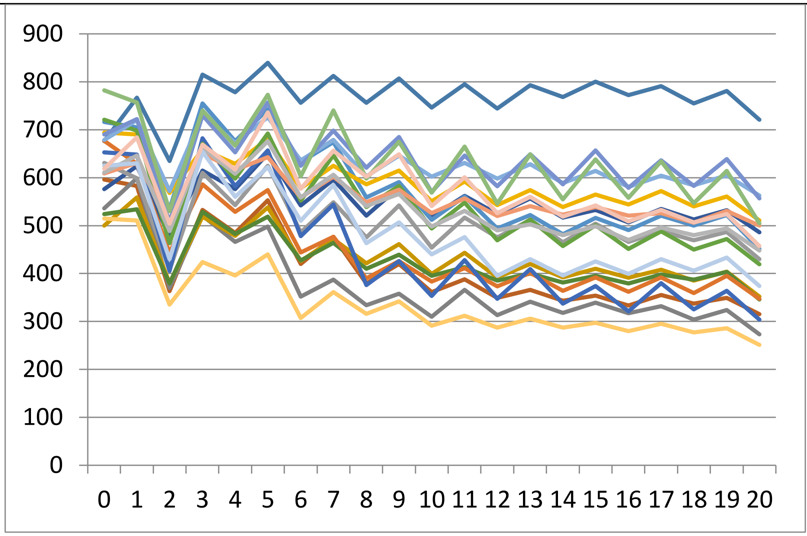
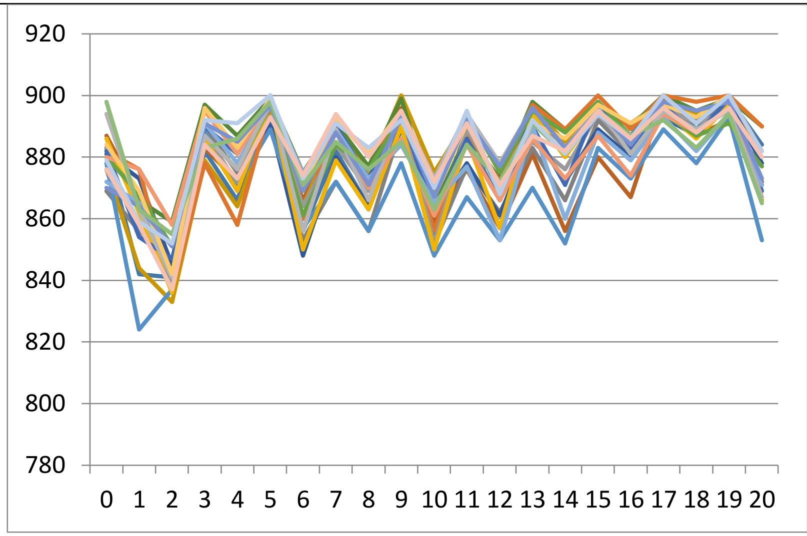
<tr><td>numberOfLand PlotUsers</td><td>
</td><td>
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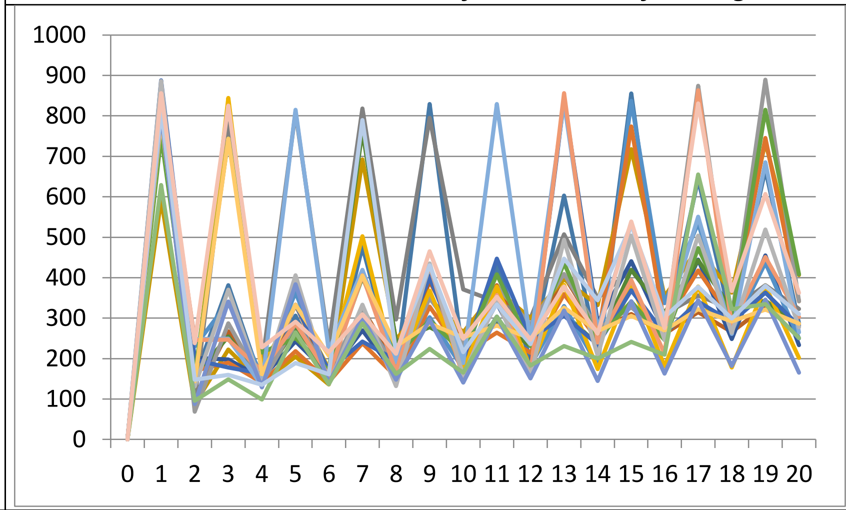
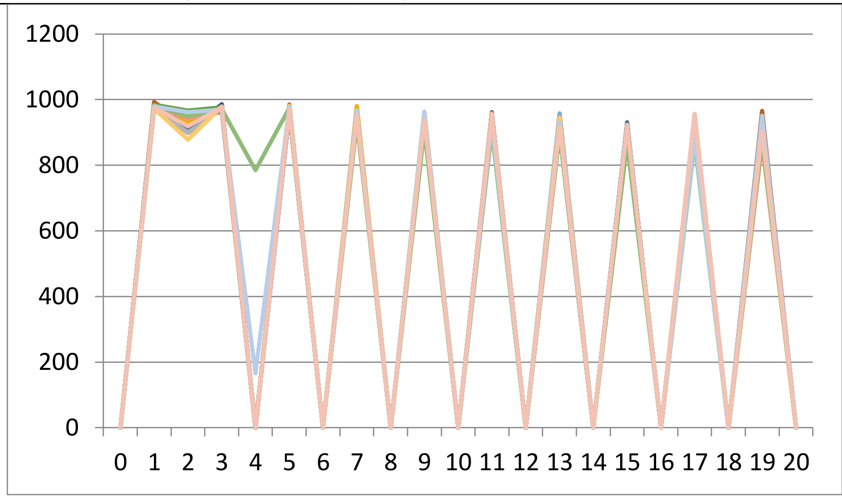
<tr><td>
</td><td>
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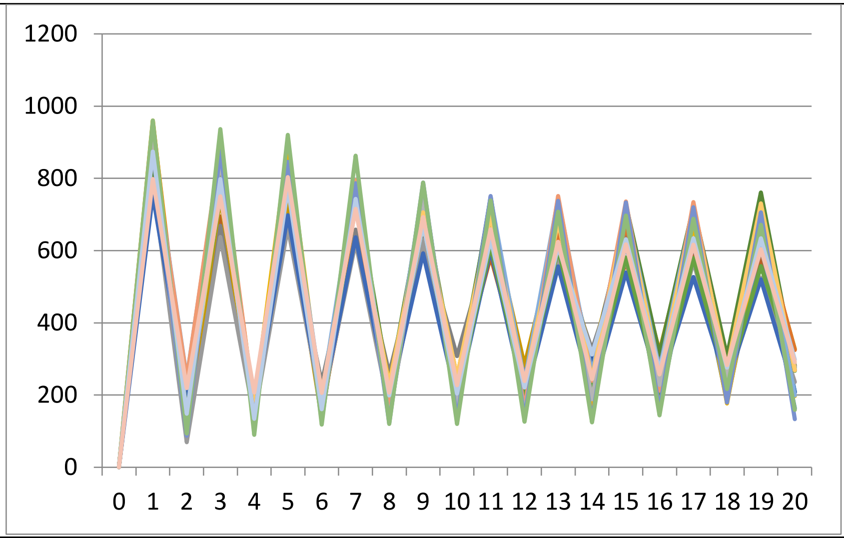
<td>
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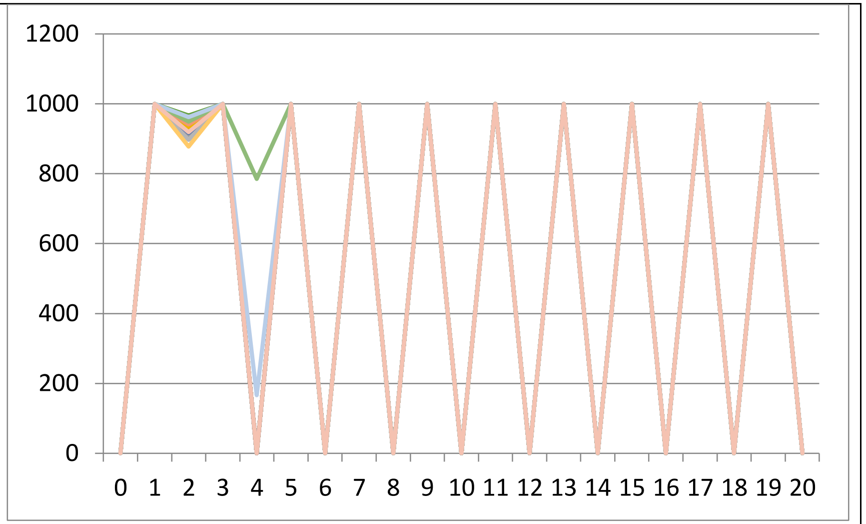
<td>
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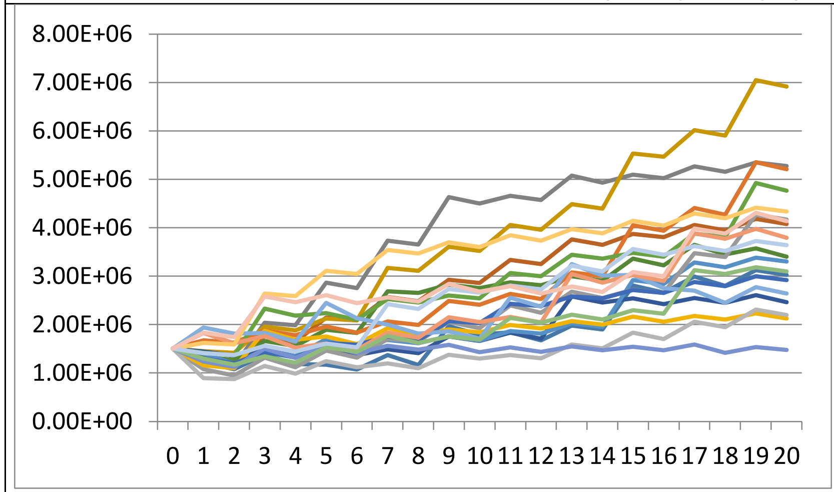
<td>
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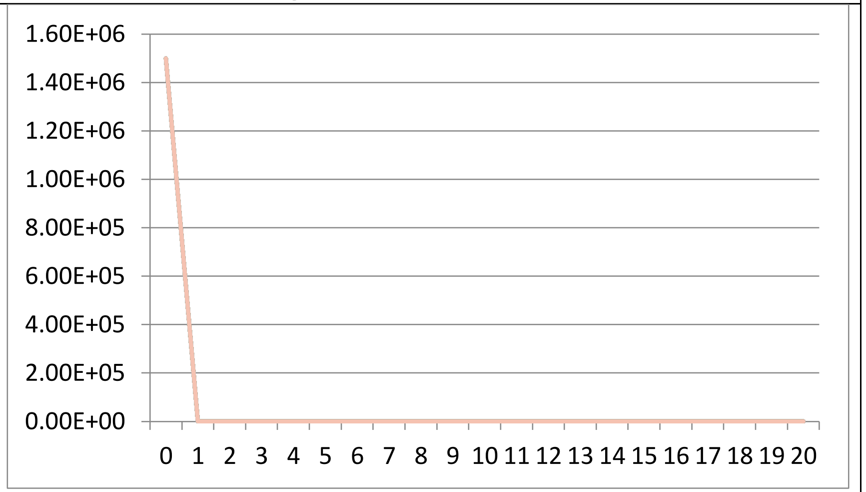
<td>
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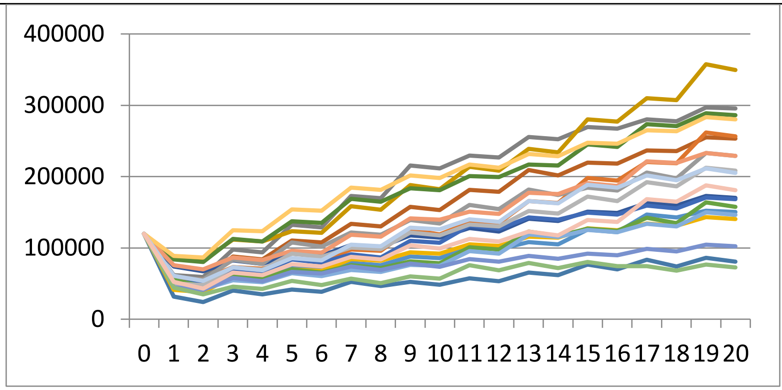
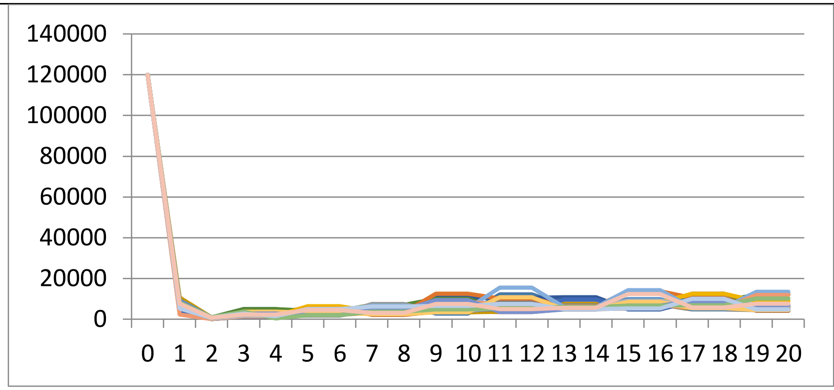
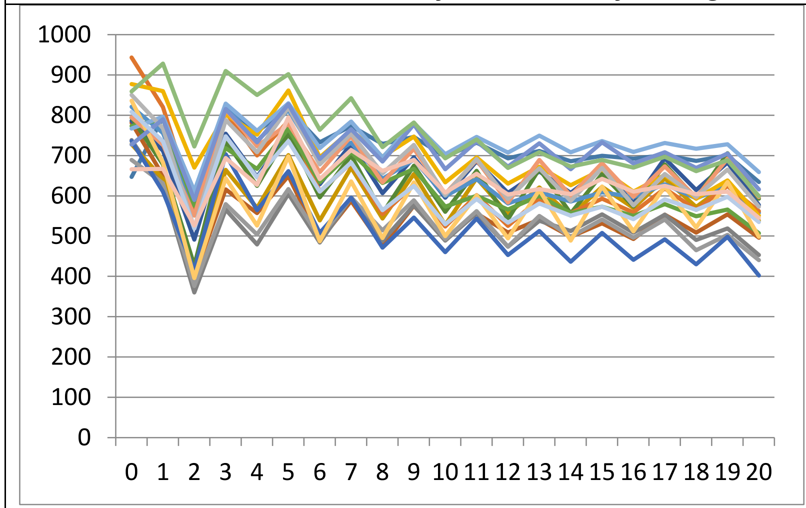
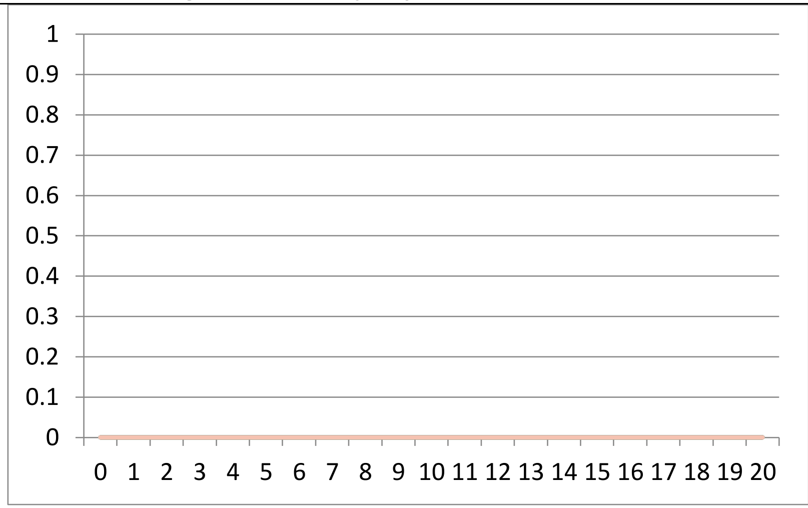
landPlotFodder		

<u>ATTACHED FIGURE 4</u>

Scenario of consistency Test Four: only environmental conservation priority logics of action for water and land regulators on an environment only composed of fertile lowlands		
Cormas Indicator	**DEFAULT SITUATION**	**STRESS TEST SITUATION**
	4.1 Evolution of the number of user agents with resource access right(s) in their portfolio over time	
numberOfUsersWith ResourceAccessRights		

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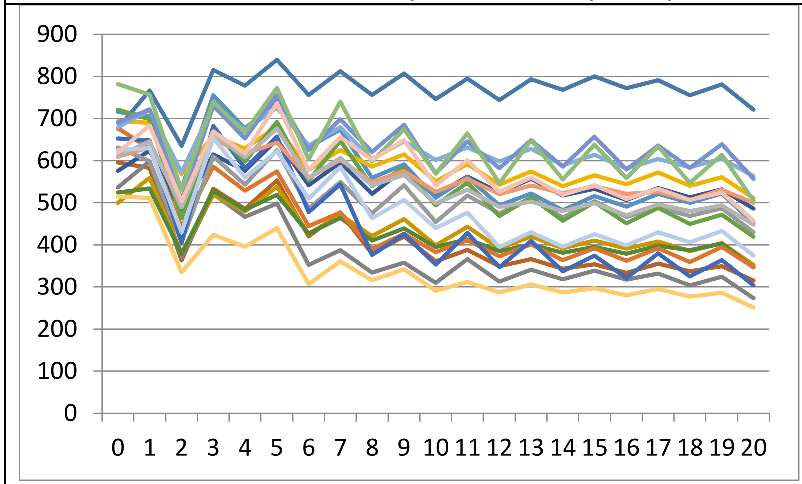
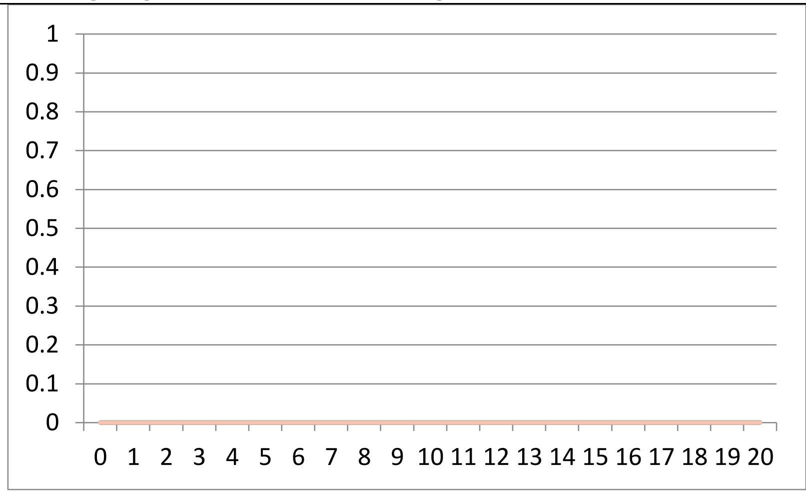
<tr><td>
</td><td>
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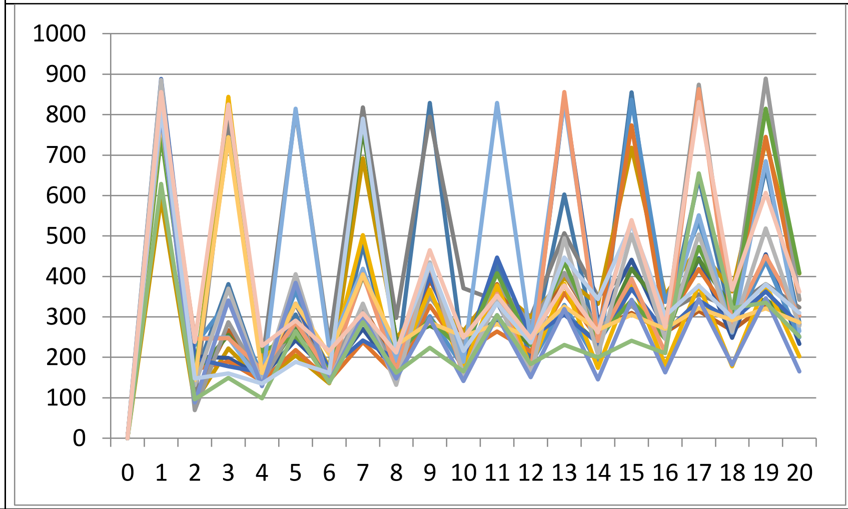
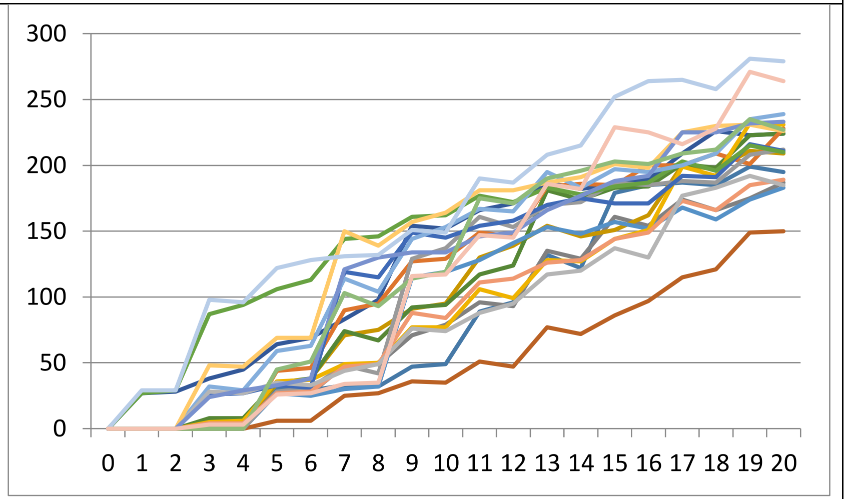
<tr><td rowspan="2">numberOfUsersWith WaterAccessRights</td><td colspan="2">***4.3 Evolution of the number of user agents with water access right(s) in their portfolio over time***</td></tr>
<tr><td>
</td><td>
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<tr><td>numberOfUsers</td><td colspan="2">***4.4 Evolution of the number of user agents realizing activities over time***</td></tr>
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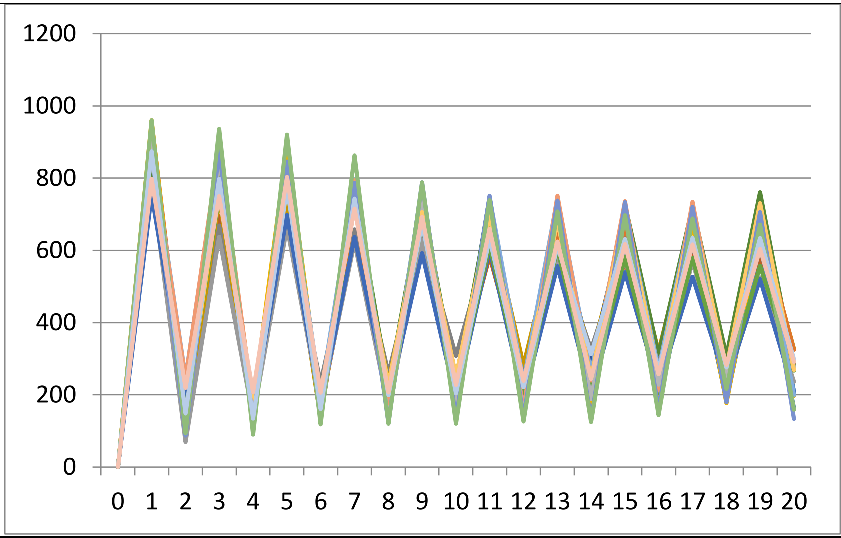
<td>
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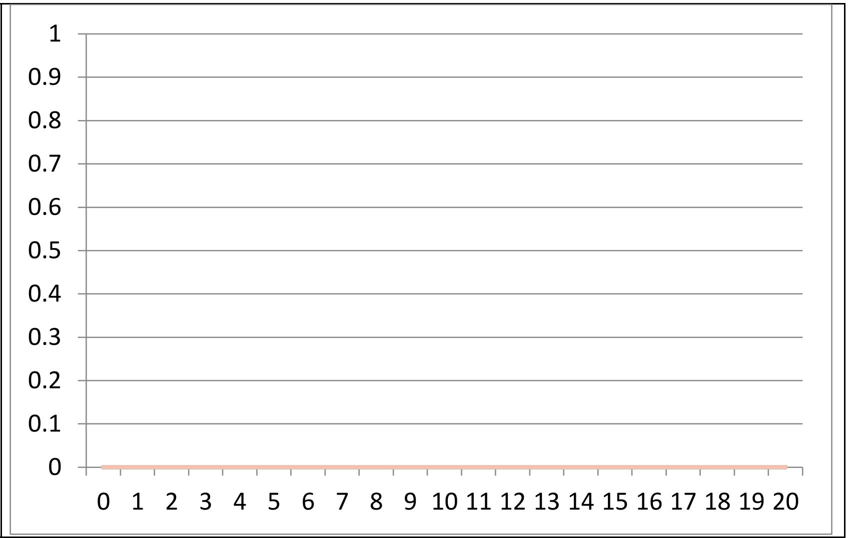
<td>
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<td colspan="2">4.5 Evolution of the quantity of water available in the drillings over time</td>
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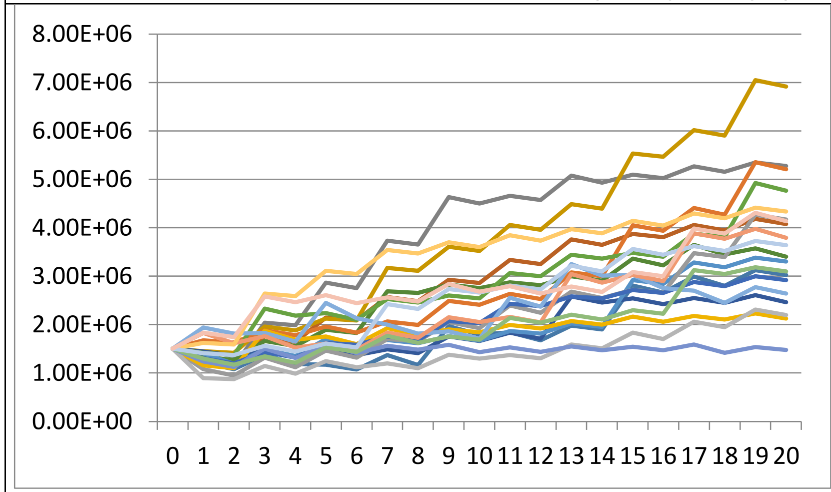
<td>
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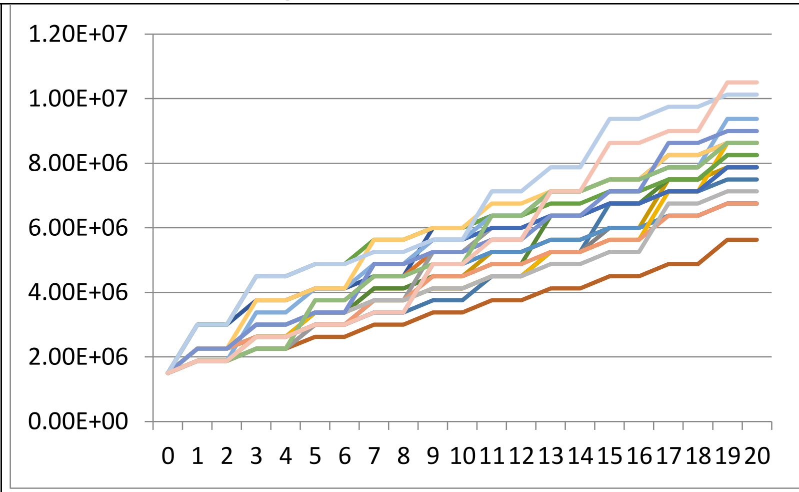
<td>
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<td colspan="2">4.6 Evolution of the quantity of fodder available on the land plots over time</td>
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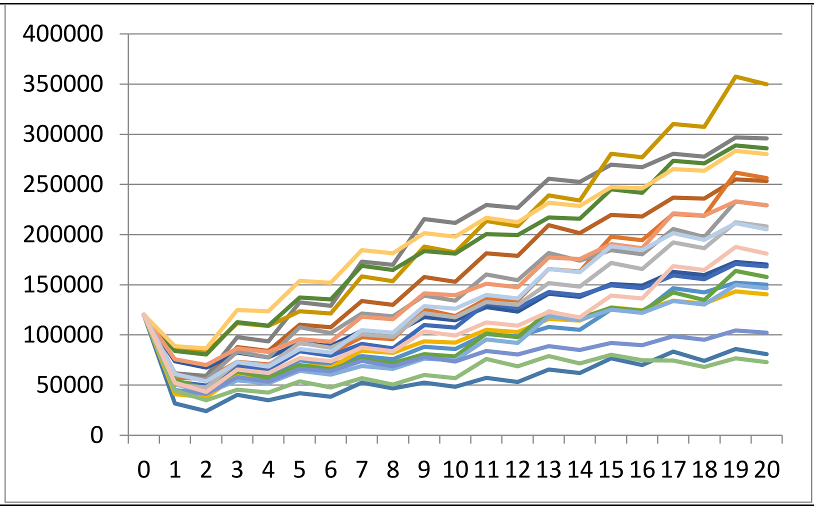
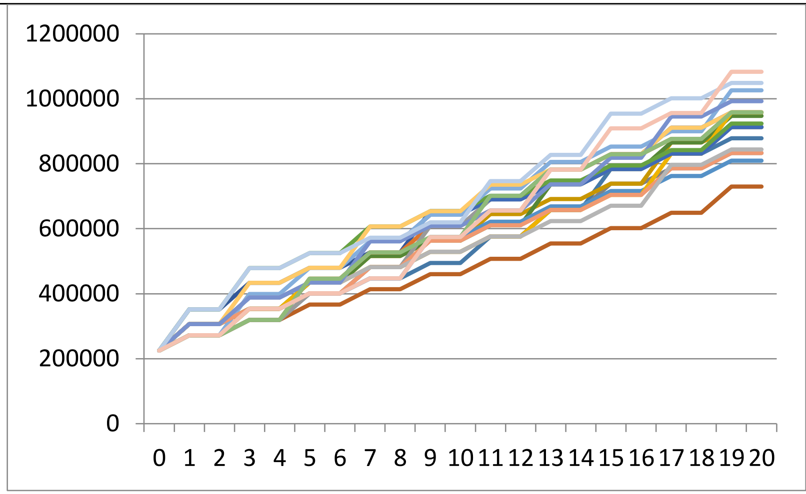
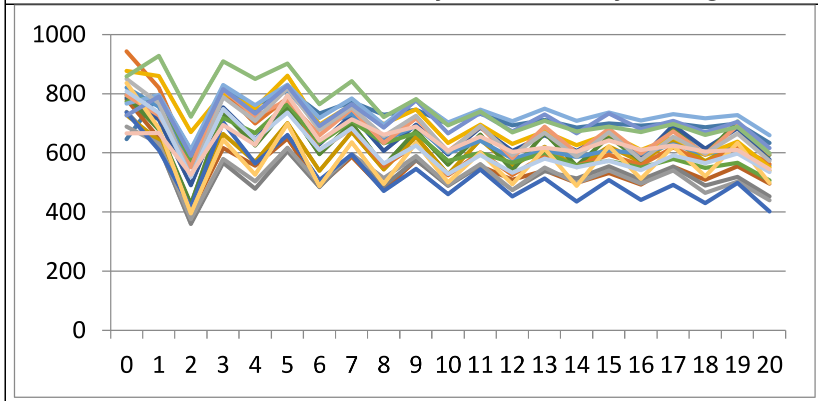
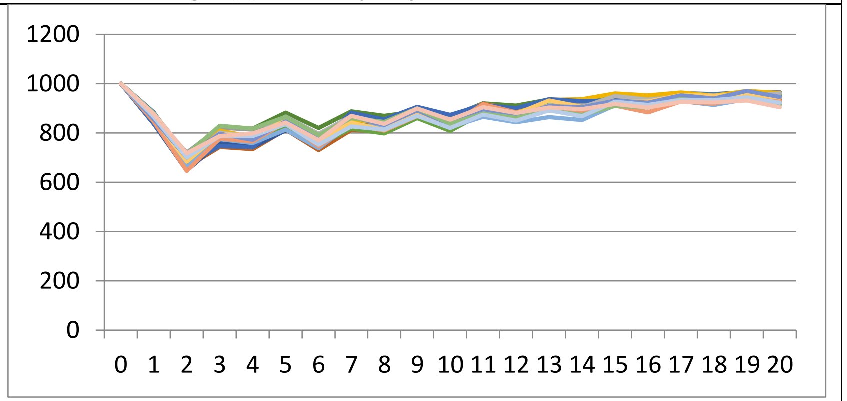
landPlotFodder		

ATTACHED FIGURE 5

Scenario of consistency Test Five: only environmental restoration priority logics of action for water and land regulators on an environment only composed of degraded soils		
Cormas Indicator	**DEFAULT SITUATION**	**STRESS TEST SITUATION**
numberOfUsersWith ResourceAccessRights	***5.1 Evolution of the number of user agents with resource access right(s) in their portfolio over time***	
		

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PlotUsers</td>
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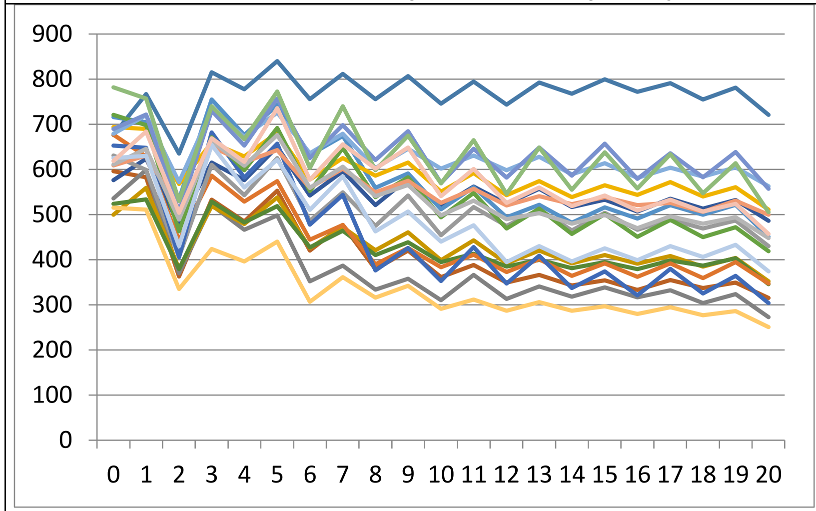
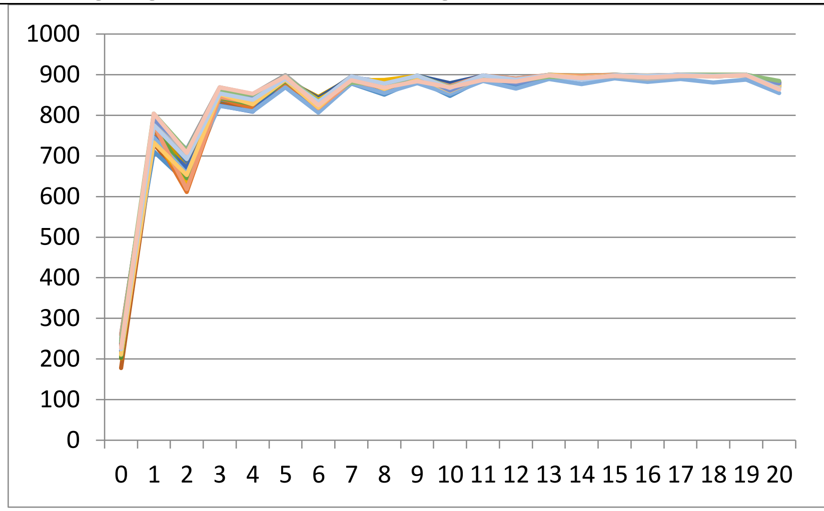
5.2 Evolution of the number of land plots concerned with ongoing user resource access rights over time





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</tr>
<tr>
<td>numberOfUsersWith
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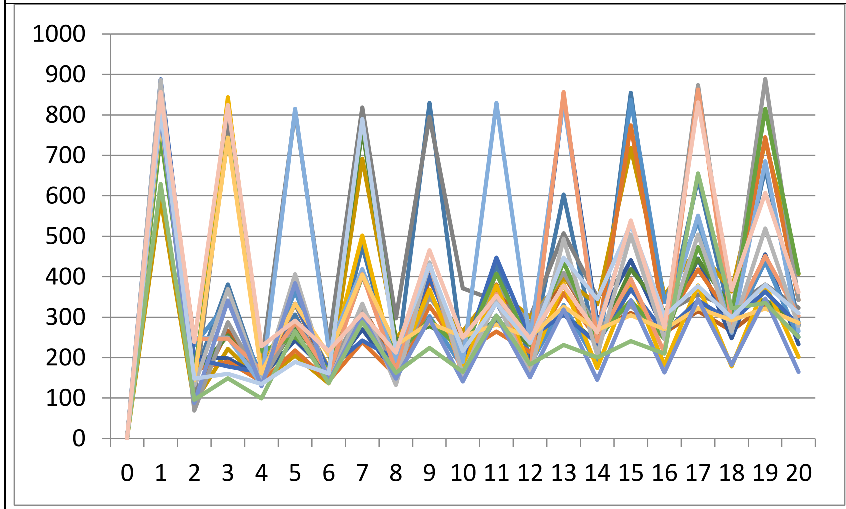
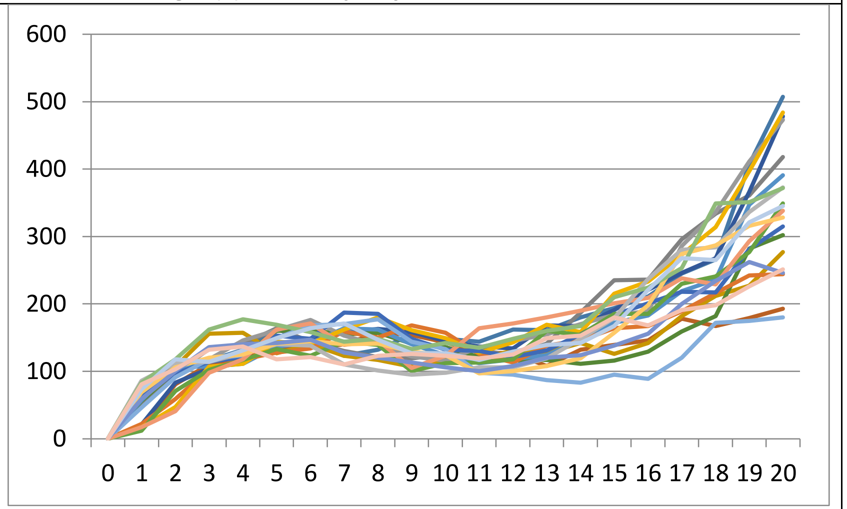
5.3 Evolution of the number of user agents with water access right(s) in their portfolio over time





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<td>numberOfUsers</td>
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5.4 Evolution of the number of user agents realizing activities over time

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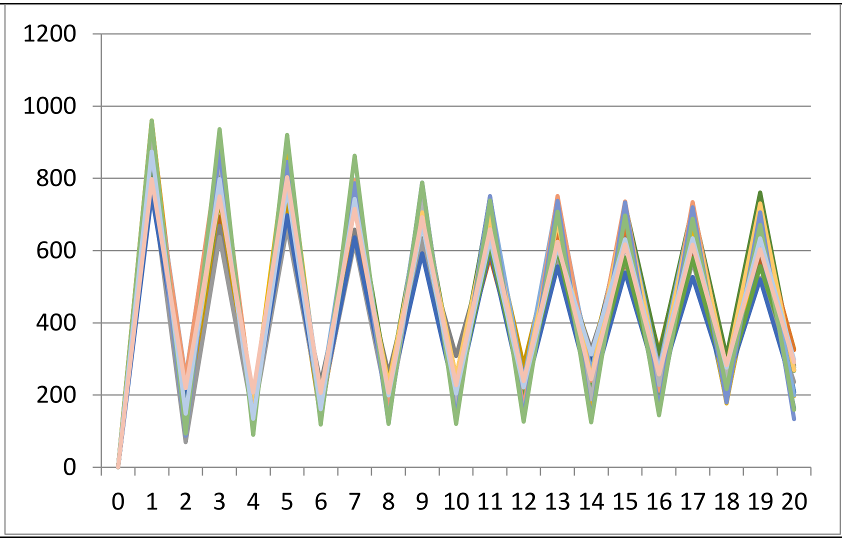
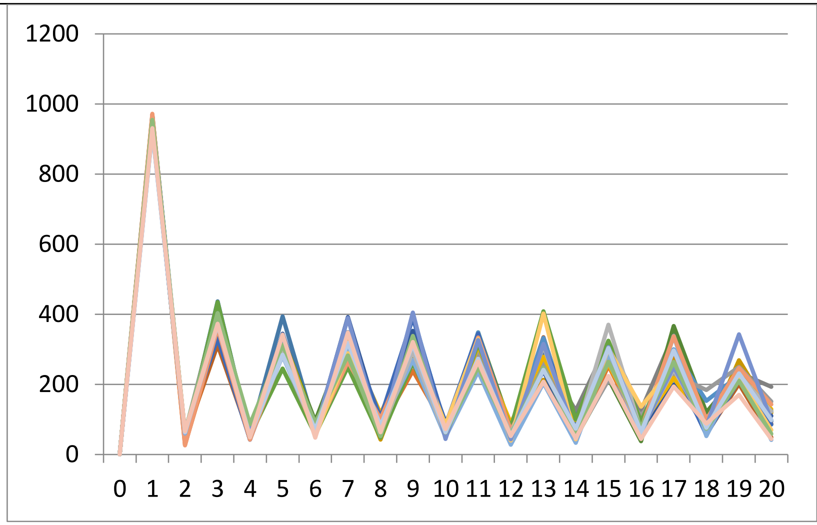
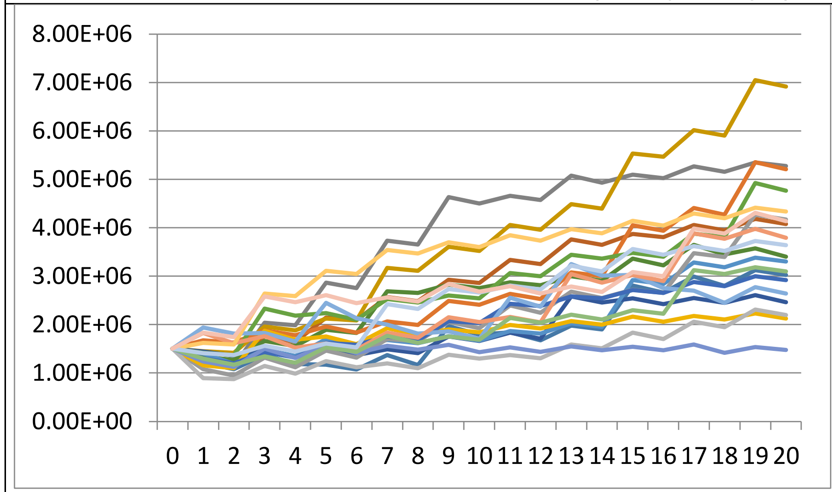
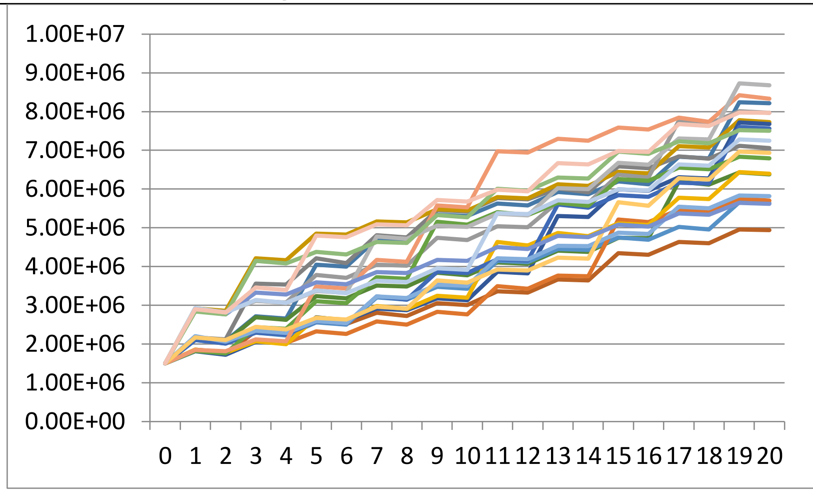
<tr><td>WithActivities</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">5.5 Evolution of the quantity of water available in the drillings over time</td></tr>
<tr><td>drillingWater Quantity</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">5.6 Evolution of the quantity of fodder available on the land plots over time</td></tr>
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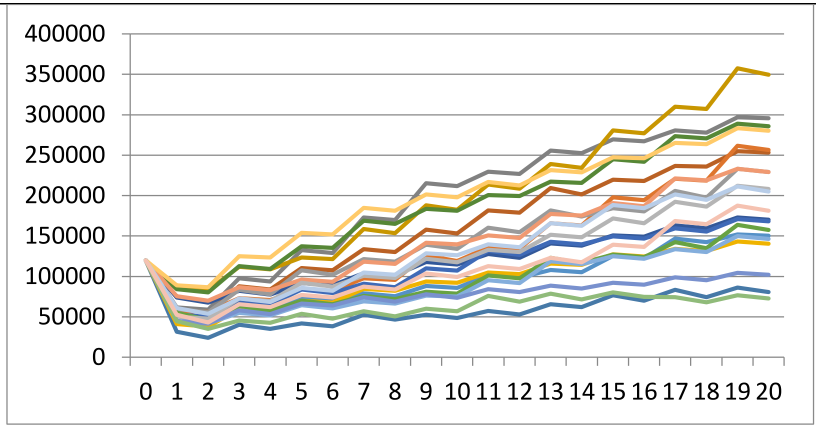
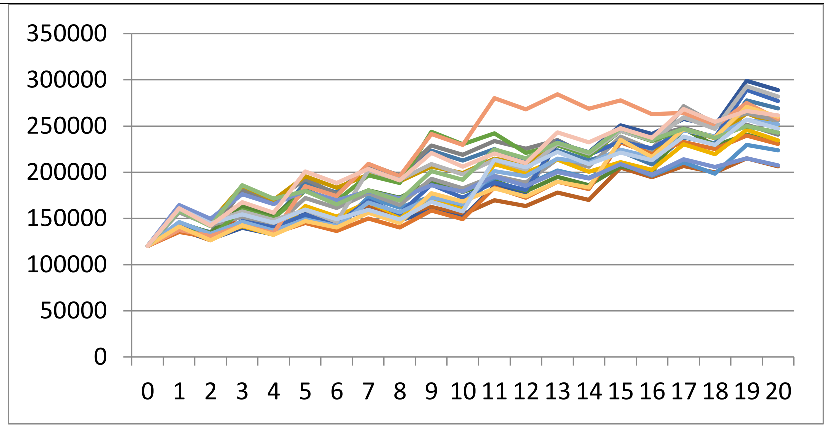
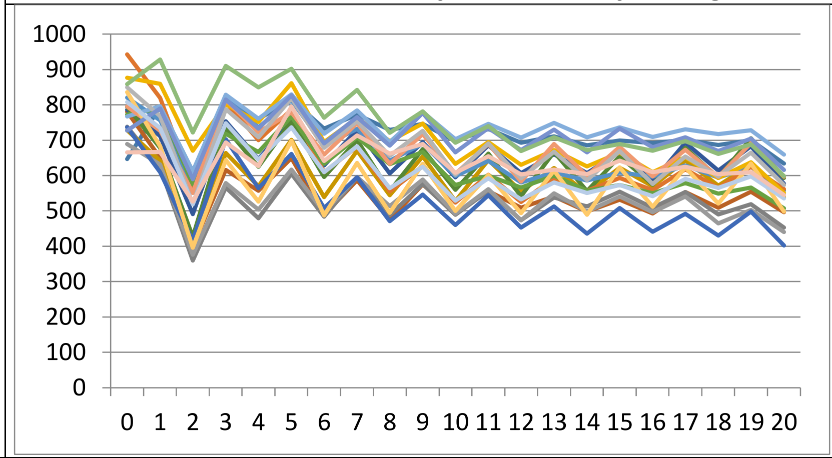
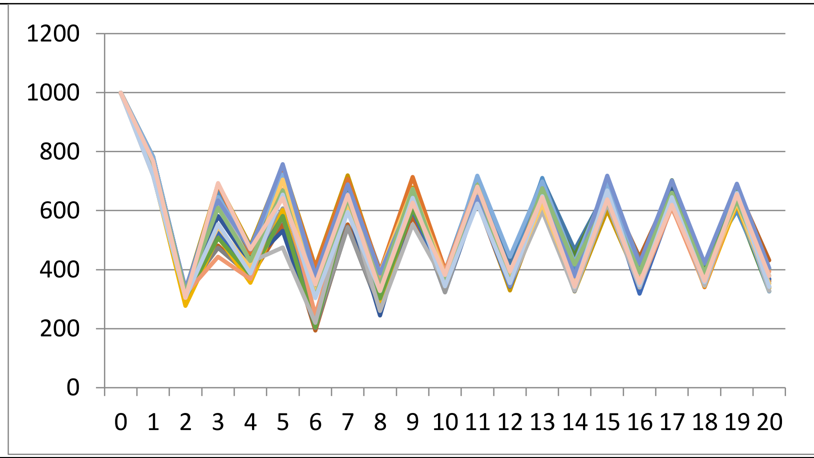
landPlotFodder		

ATTACHED FIGURE 6

Scenario of consistency Test Six: only economic priority logics of action for water and land regulators, with only high water and land access prices		
Cormas Indicator	**DEFAULT SITUATION**	**STRESS TEST SITUATION**
	6.1 Evolution of the number of user agents with resource access right(s) in their portfolio over time	
numberOfUsersWith ResourceAccessRights		
	6.2 Evolution of the number of land plots concerned with ongoing user resource access rights over time	

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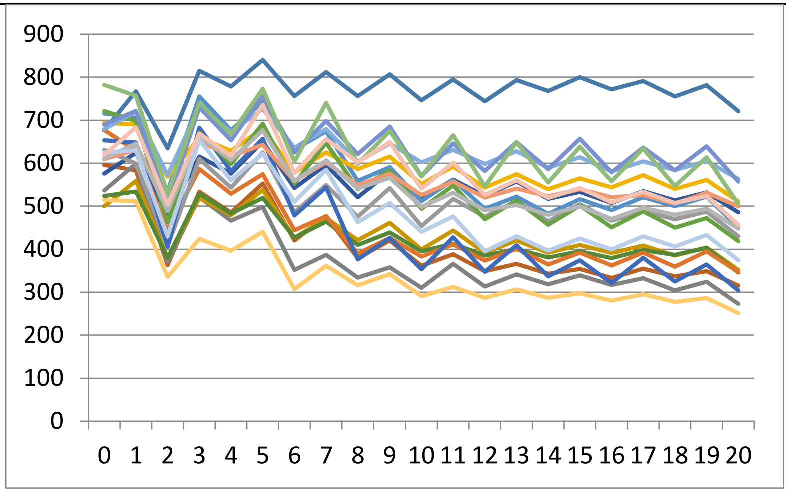
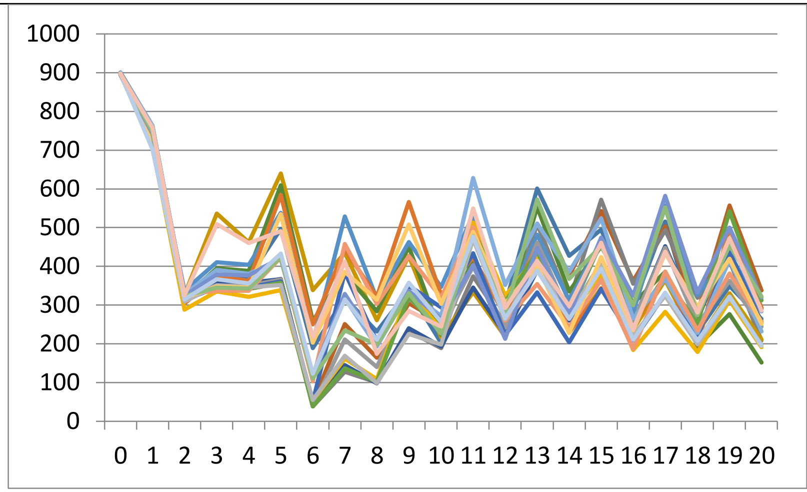
PlotUsers</td><td>
</td><td>
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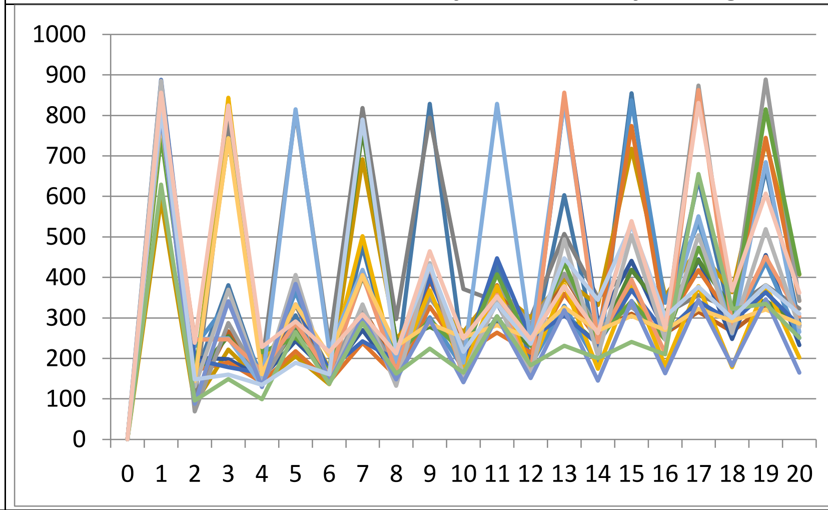
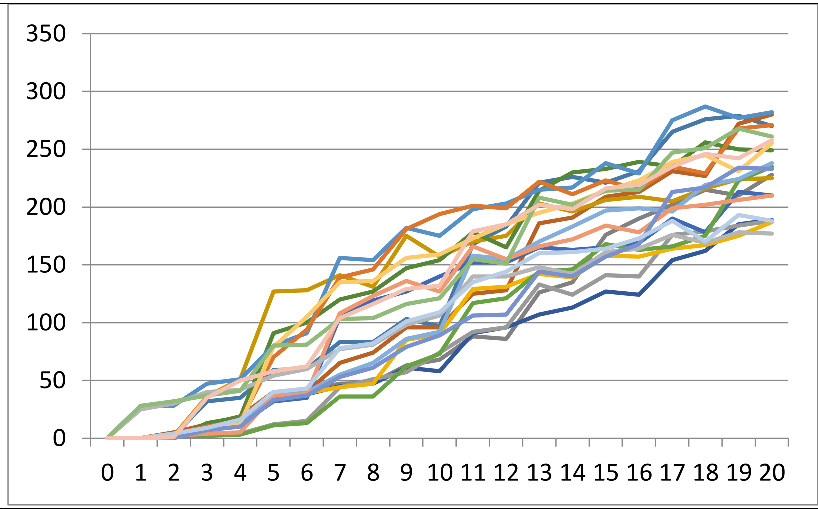
<tr><td>
</td><td>
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<tr><td>numberOfUsers</td><td colspan="2">6.4 Evolution of the number of user agents realizing activities over time</td></tr>
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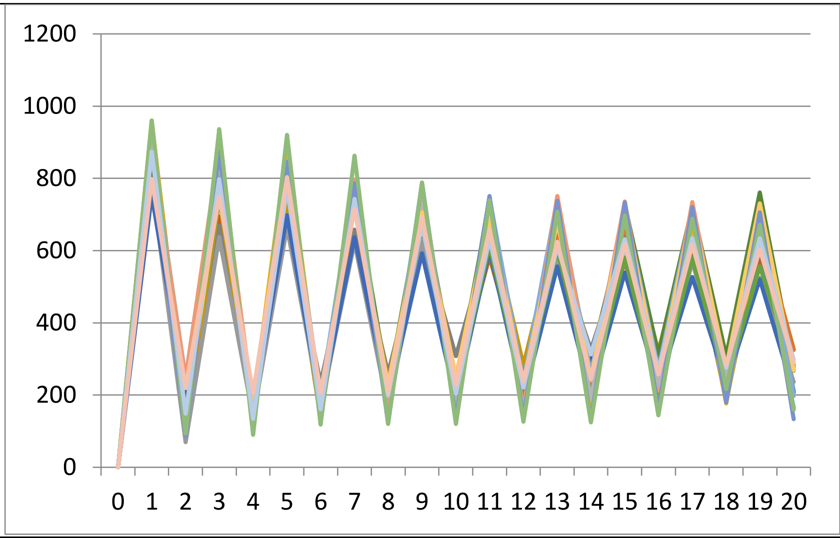
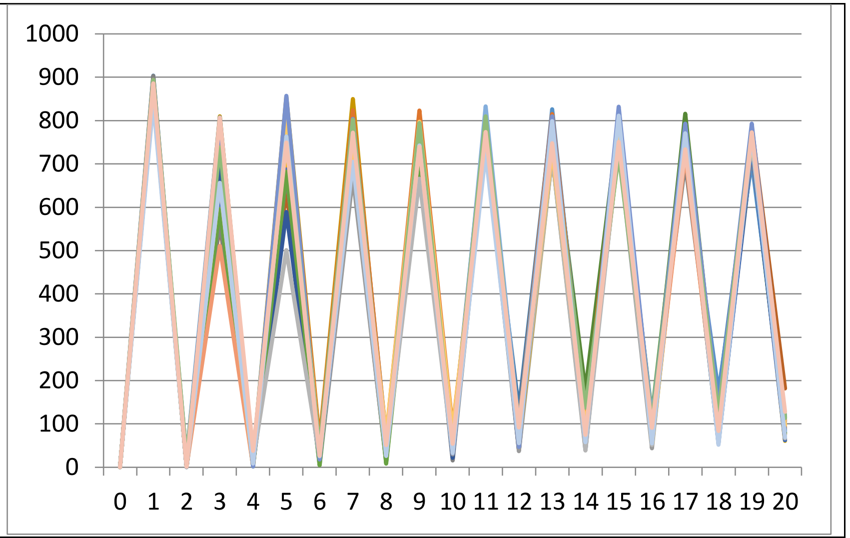
<tr><td>WithActivities</td><td>
</td><td>
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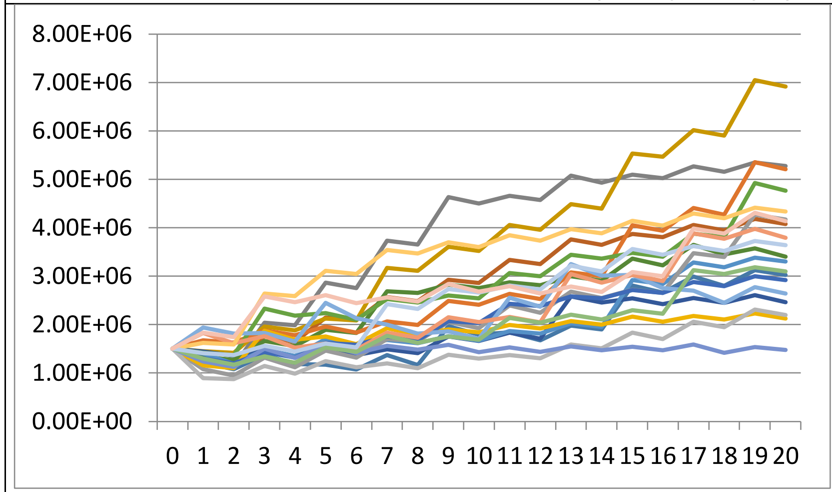
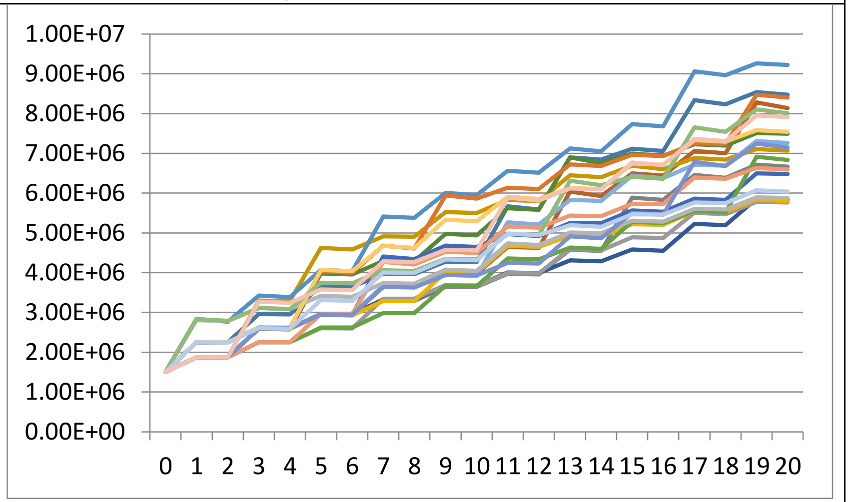
<tr><td>drillingWater Quantity</td><td>
</td><td>
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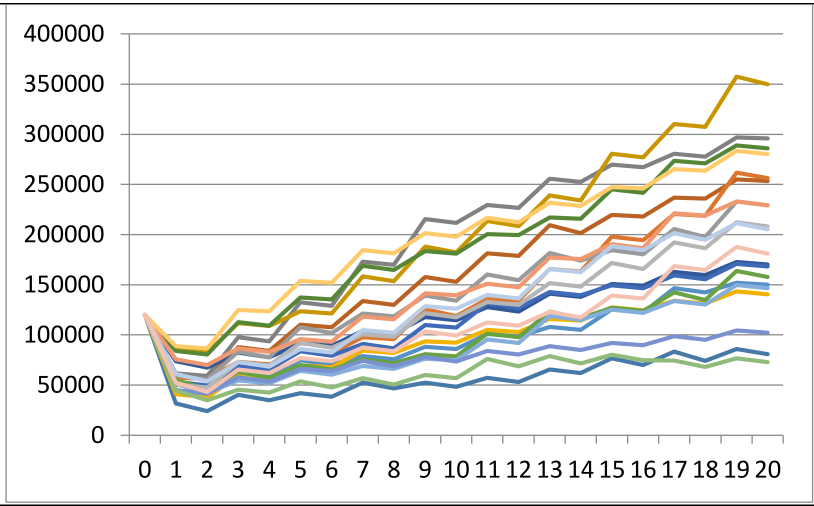
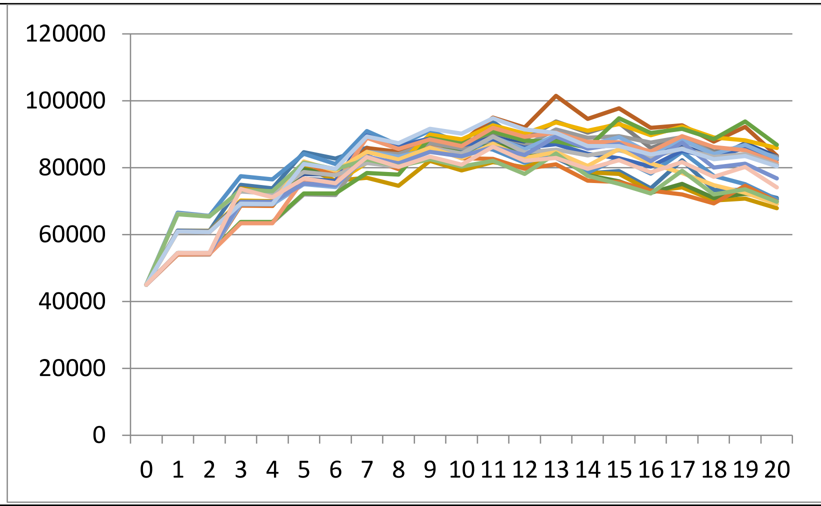
landPlotFodder		

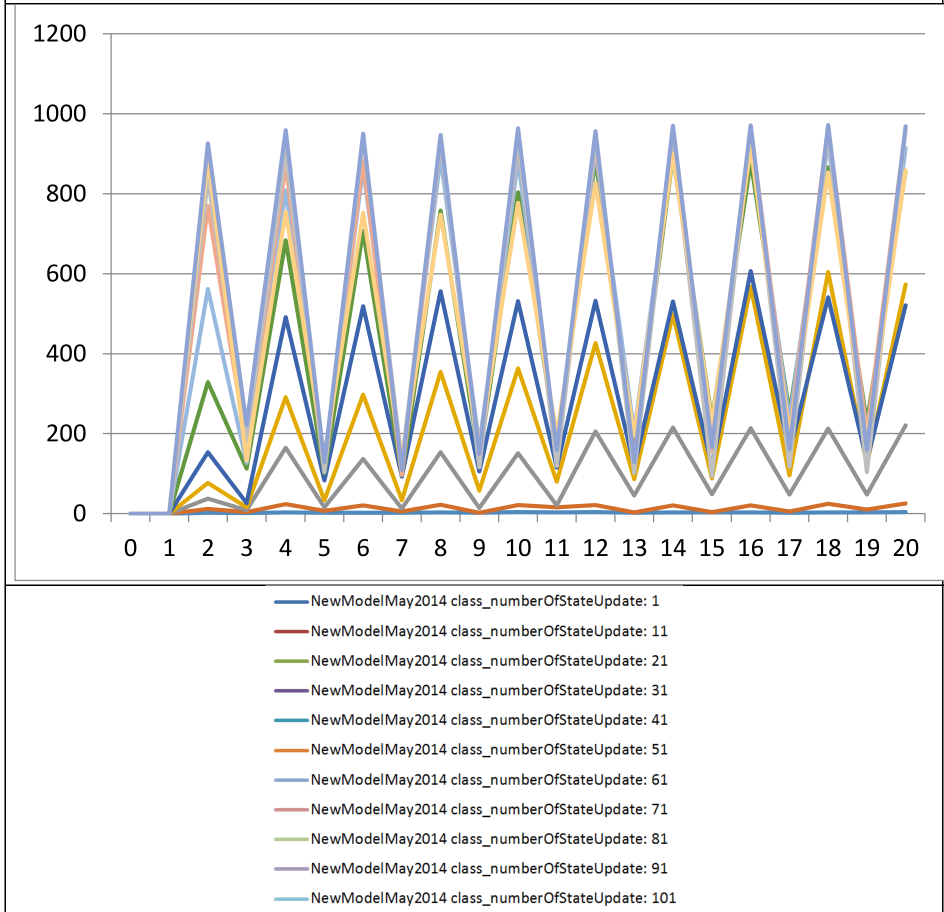
ATTACHED FIGURE A

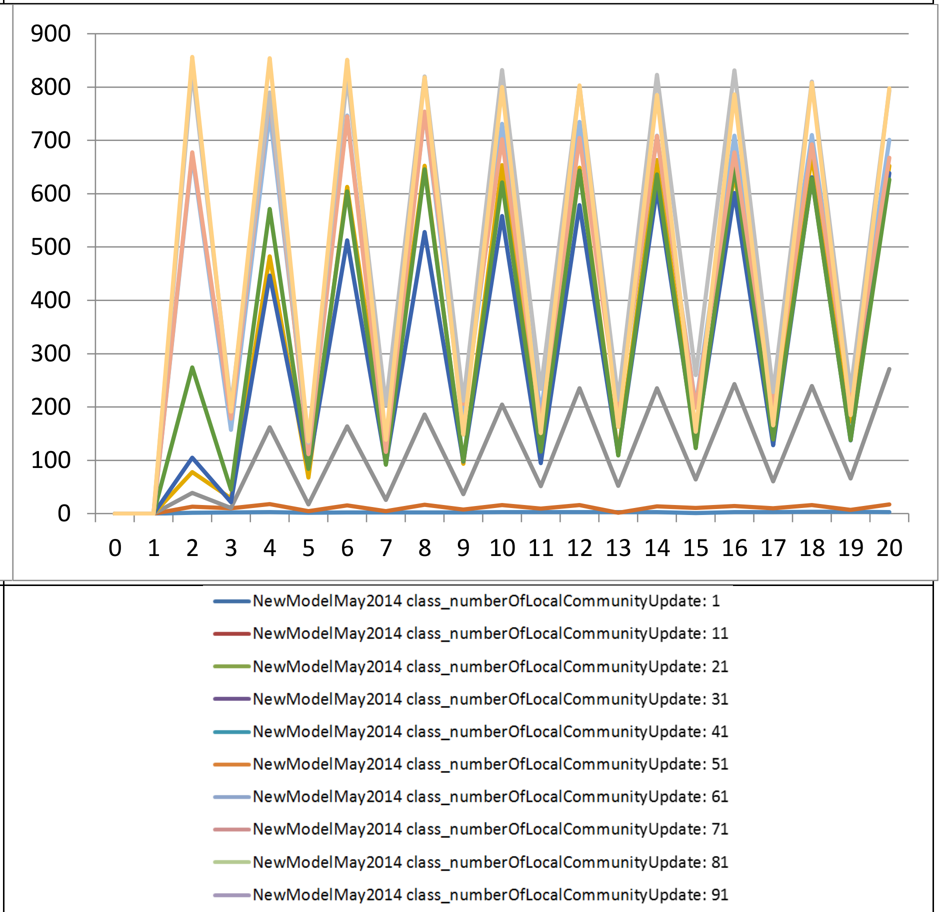
FIGURE A

Randomly spread introduction pattern of a fixed intensity and a variable distribution of a new land regulation

PANEL 1 : comparison of the diffusion of the State and Local Community new land regulations on the user agents rural activities

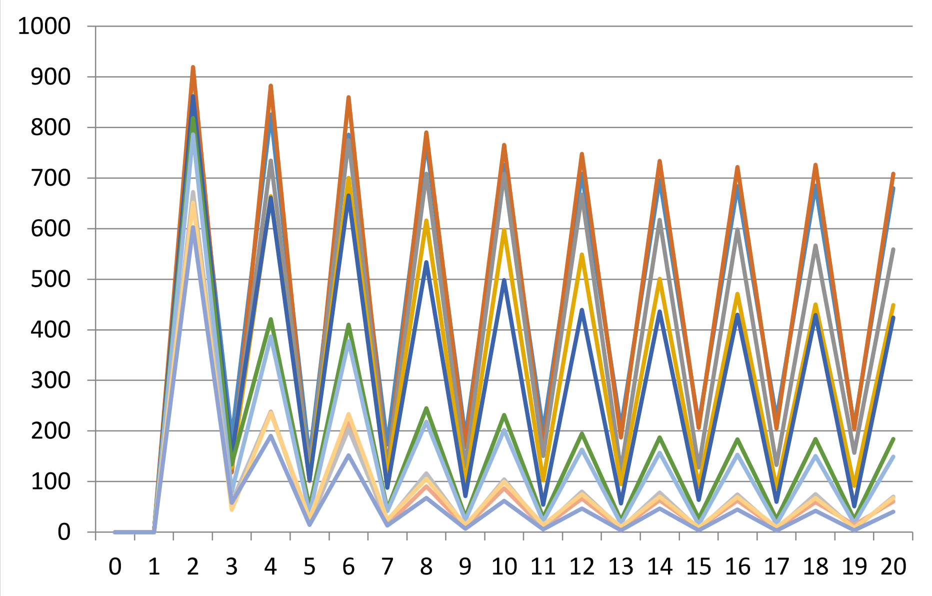
Level of rural activities initiated by user agents over time through state resource access rights	*Level of rural activities initiated by user agents over time through local community resource access rights*





PANEL 2: impact of these new land regulations introduction patterns on the initial traditional land chief regulation

Level of rural activities initiated by user agents over time through land chief resource access rights when a new State land regulation is introduced



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NewModelMay2014 class_numberOfStateUpdate: 71
NewModelMay2014 class_numberOfStateUpdate: 81
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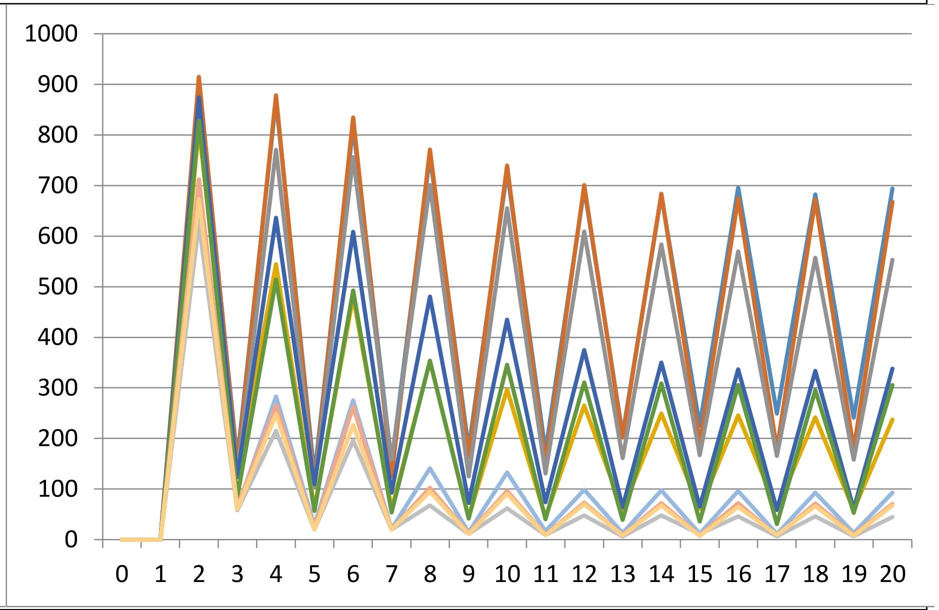
Level of rural activities initiated by user agents over time through land chief resource access rights when a new local community land regulation is introduced



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NewModelMay2014 class_numberOfLocalCommunityUpdate: 61
NewModelMay2014 class_numberOfLocalCommunityUpdate: 71
NewModelMay2014 class_numberOfLocalCommunityUpdate: 81
NewModelMay2014 class_numberOfLocalCommunityUpdate: 91

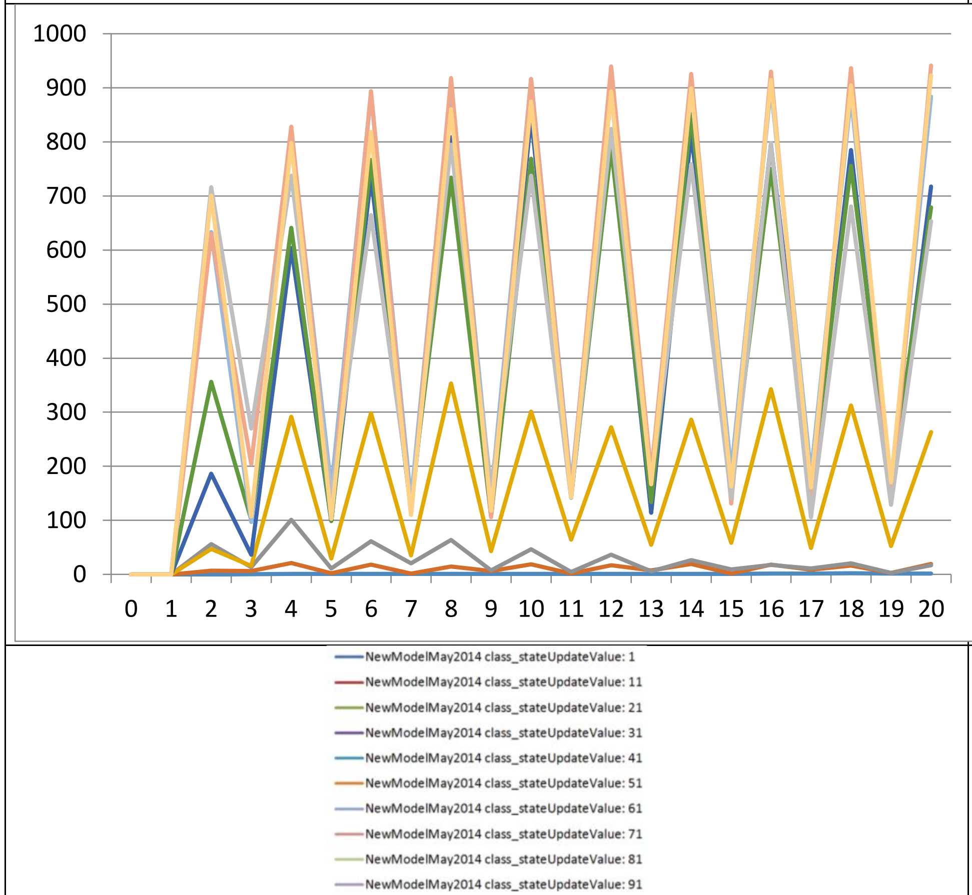
ATTACHED FIGURE B

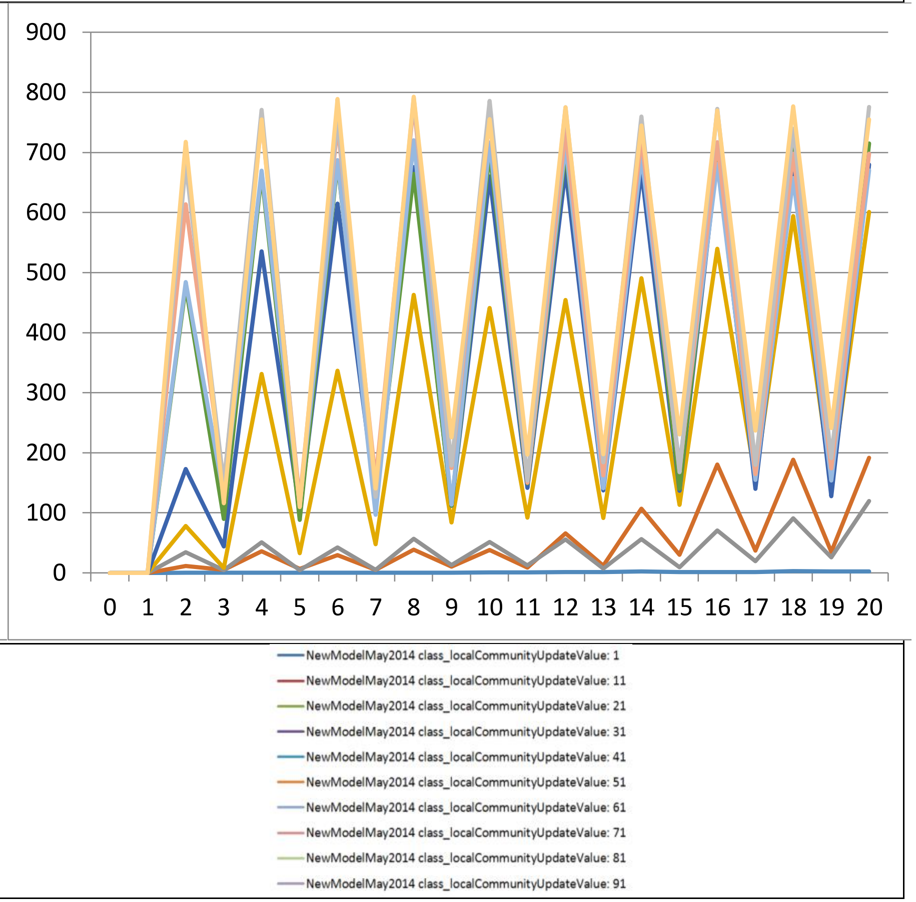
FIGURE B

Randomly spread introduction pattern of a fixed distribution and a variable intensity of a new land regulation

PANEL 1 : comparison of the diffusion of the State and Local Community new land regulations on the user agents rural activities

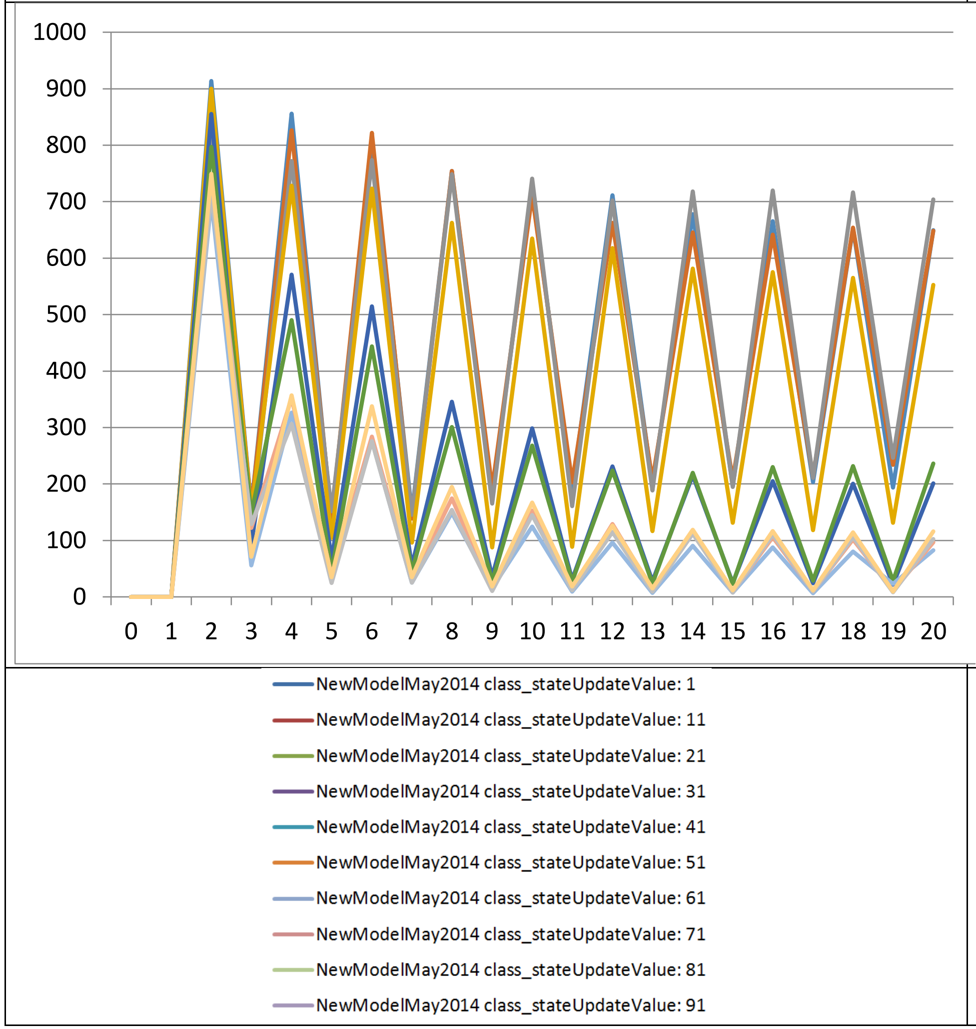
Level of rural activities initiated by user agents over time through state resource access rights	*Level of rural activities initiated by user agents over time through local community resource access rights*

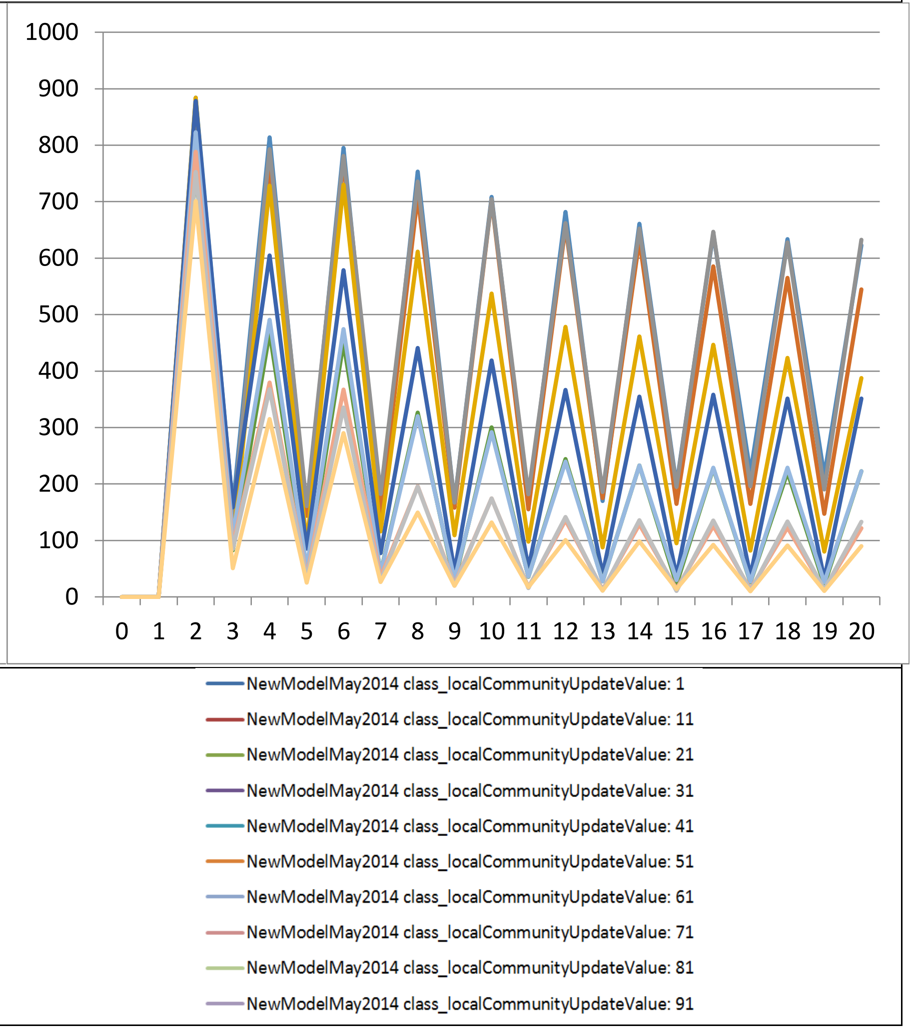




PANEL 2: impact of these new land regulations introduction patterns on the initial traditional land chief regulation

Level of rural activities initiated by user agents over time through land chief resource access rights when a new State land regulation is introduced	*Level of rural activities initiated by user agents over time through land chief resource access rights when a new local community land regulation is introduced*



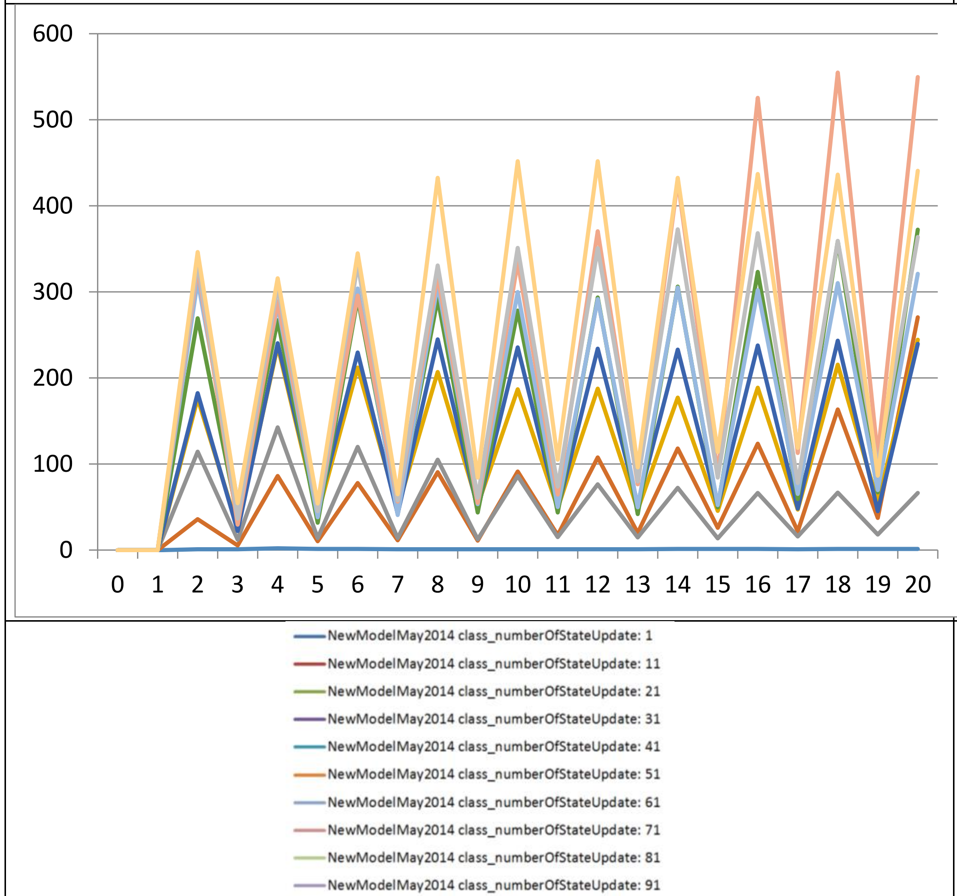
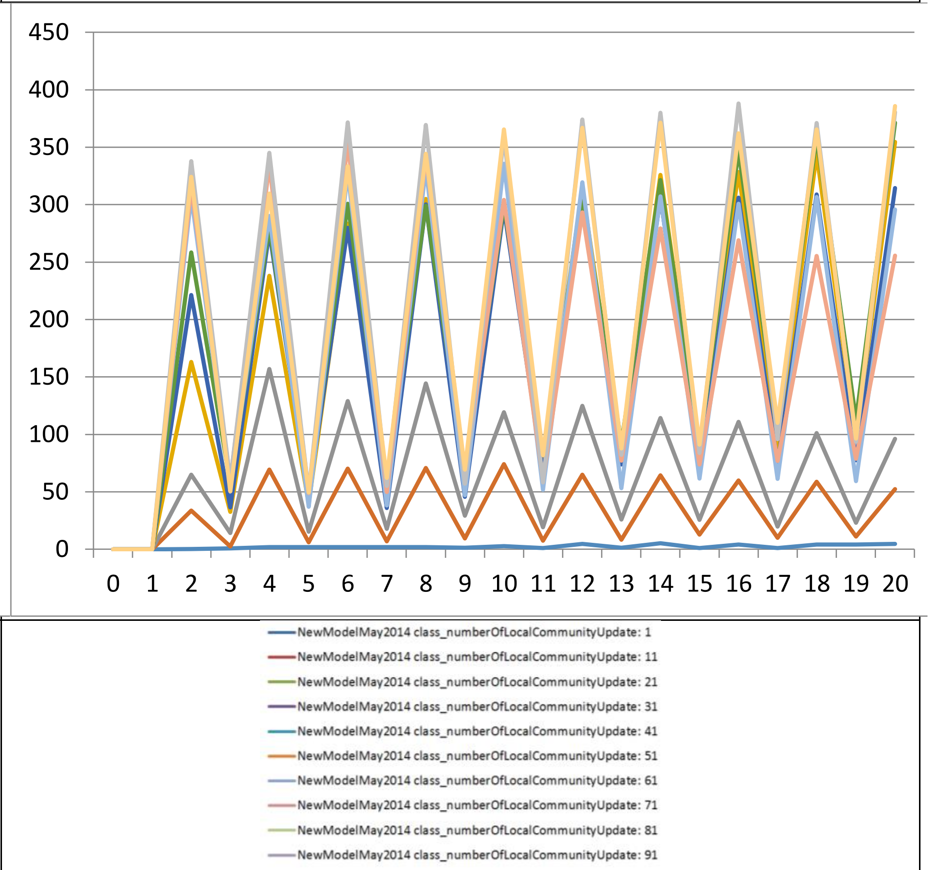


ATTACHED FIGURE C

FIGURE C

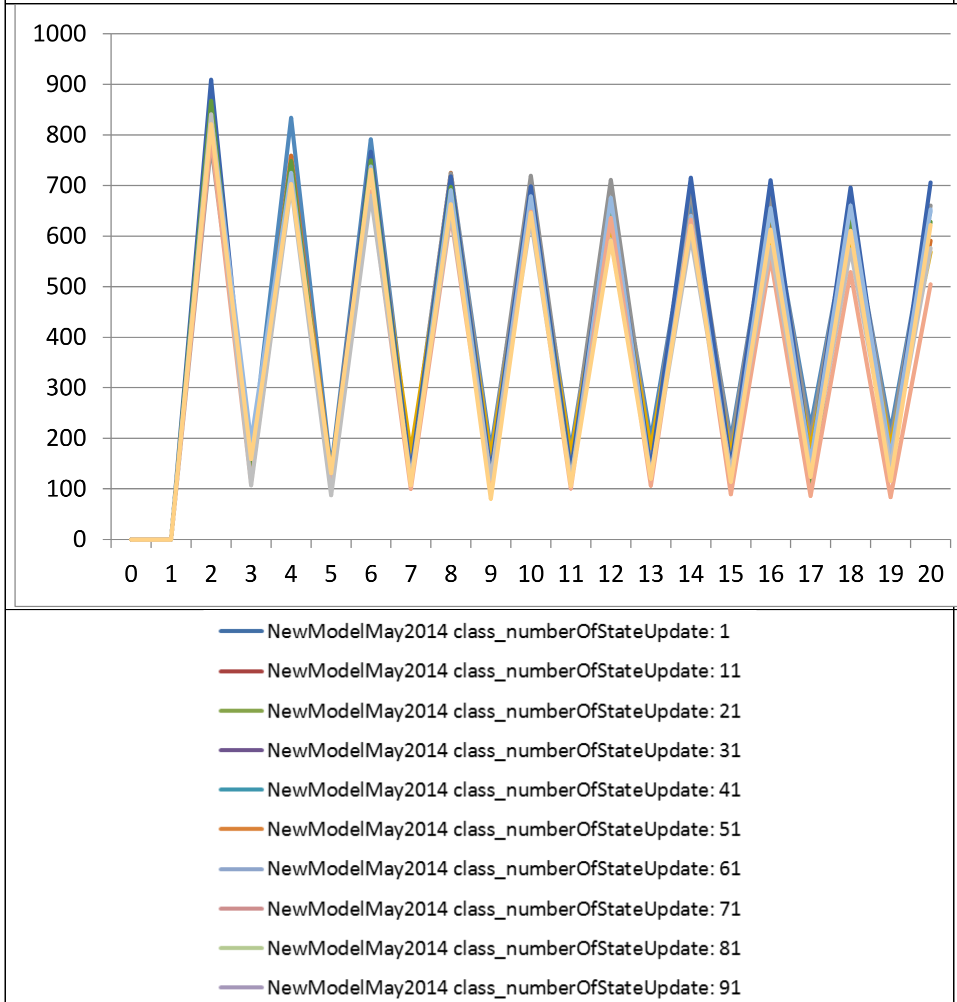
Contiguous-localized introduction pattern of a fixed intensity and a variable distribution of a new land regulation

PANEL 1 : comparison of the diffusion of the State and Local Community new land regulations on the user agents rural activities

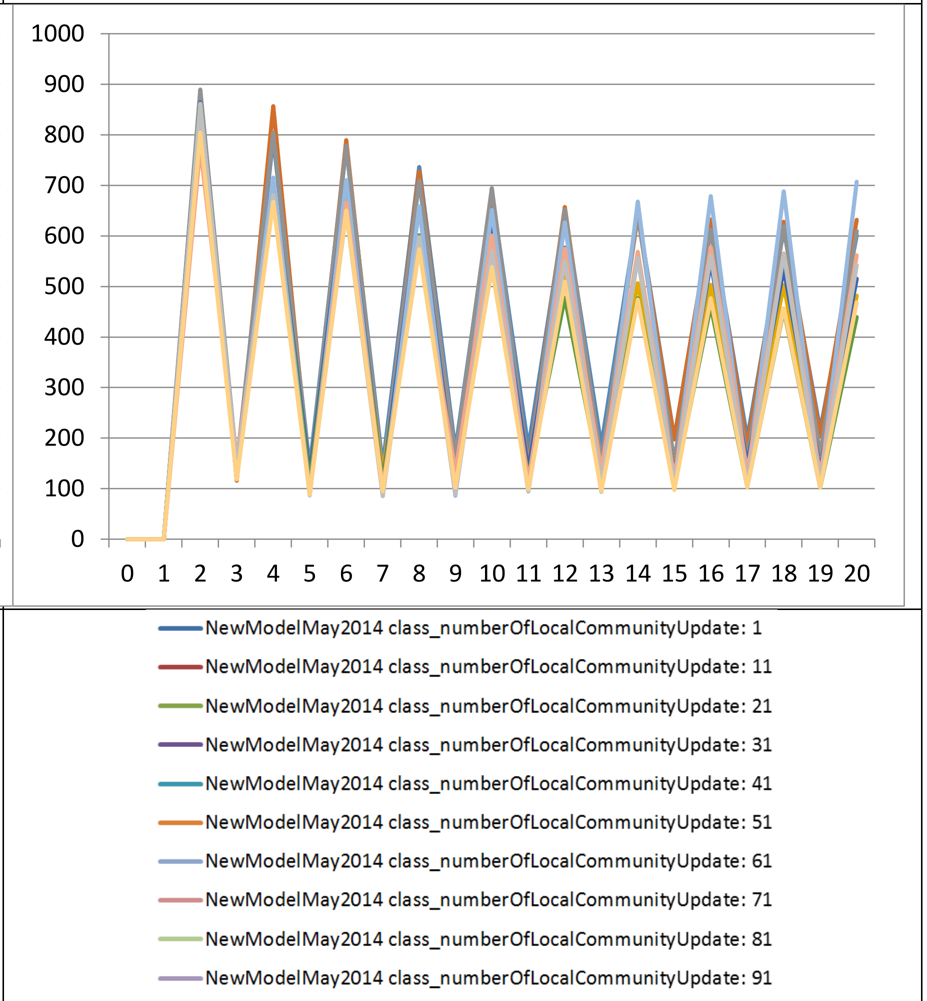
Level of rural activities initiated by user agents over time through state resource access rights	*Level of rural activities initiated by user agents over time through local community resource access rights*
	

PANEL 2: impact of these new land regulations introduction patterns on the initial traditional land chief regulation

Level of rural activities initiated by user agents over time through land chief resource access rights when a new State land regulation is introduced



Level of rural activities initiated by user agents over time through land chief resource access rights when a new local community land regulation is introduced



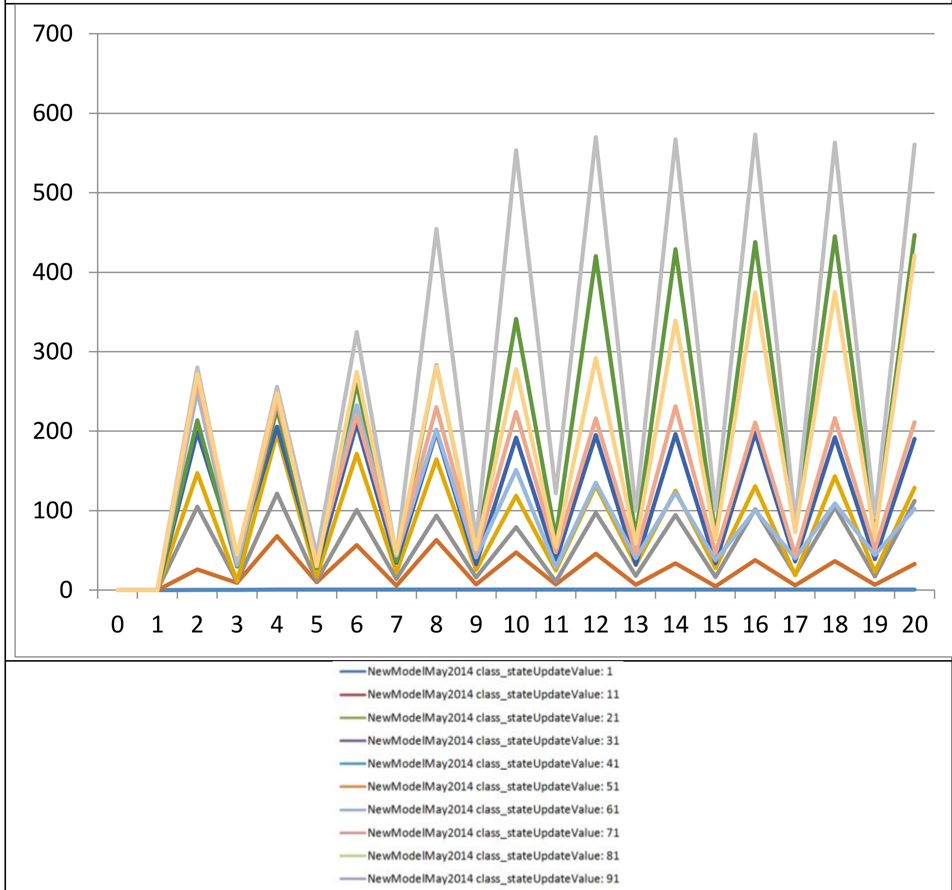
ATTACHED FIGURE D

FIGURE D

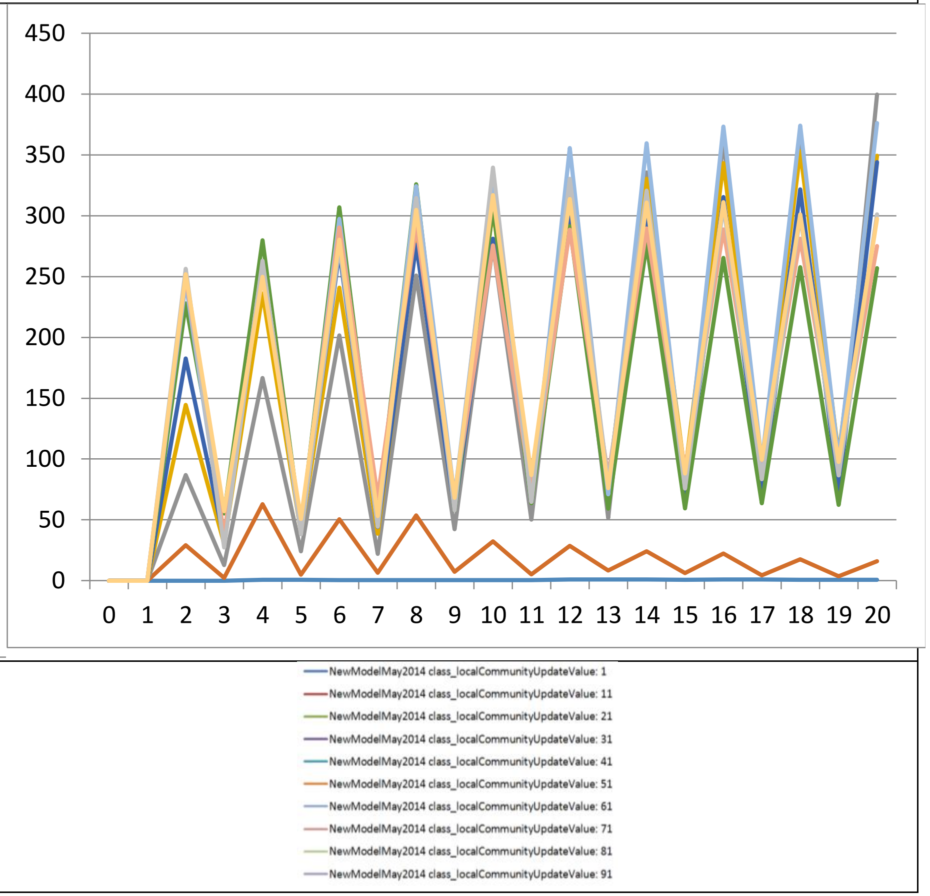
Contiguous-localized introduction pattern of a fixed distribution and a variable intensity of a new land regulation

PANEL 1 : comparison of the diffusion of the State and Local Community new land regulations on the user agents rural activities

Level of rural activities initiated by user agents over time through state resource access rights

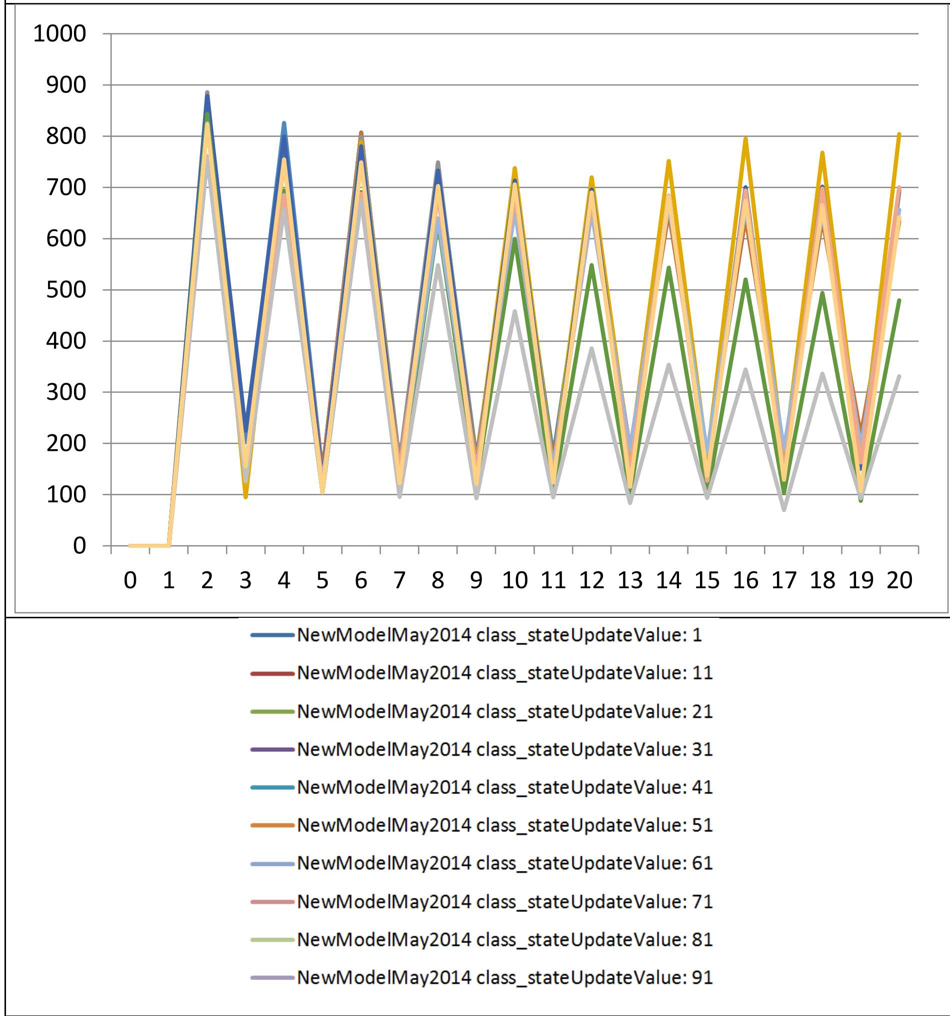


Level of rural activities initiated by user agents over time through local community resource access rights

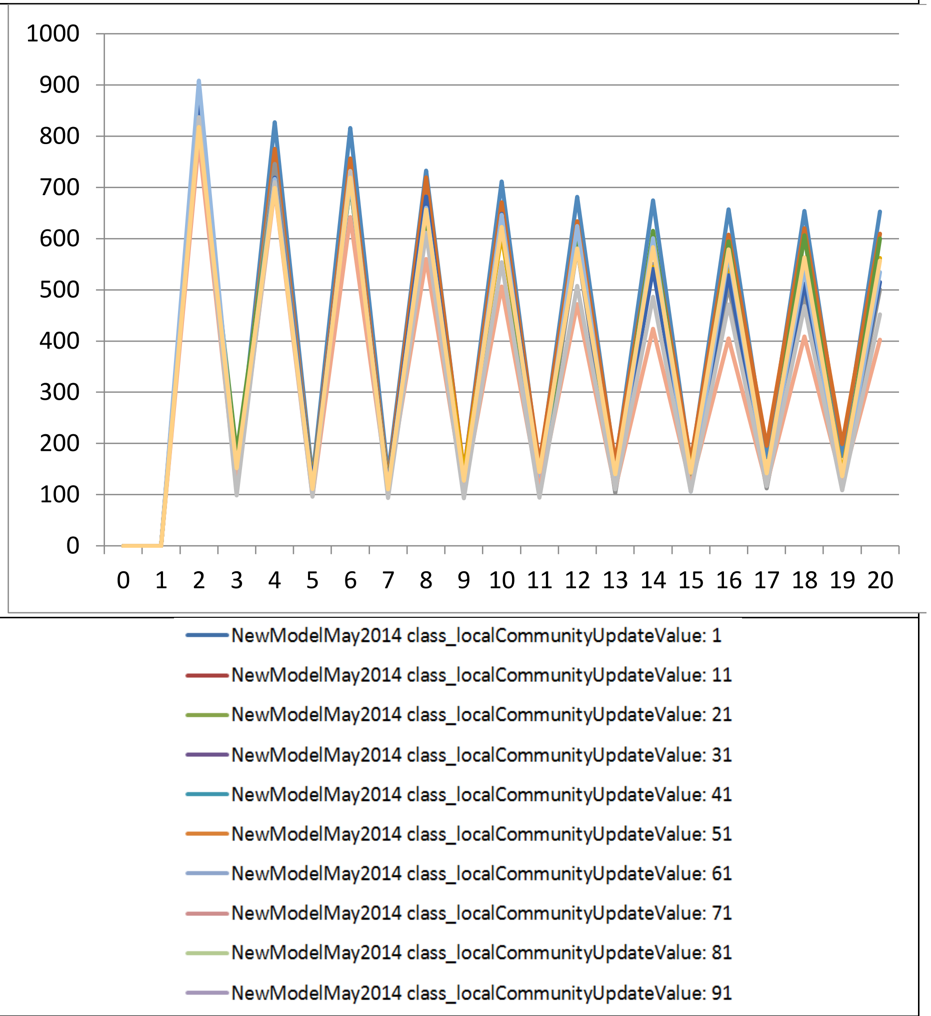


PANEL 2: impact of these new land regulations introduction patterns on the initial traditional land chief regulation

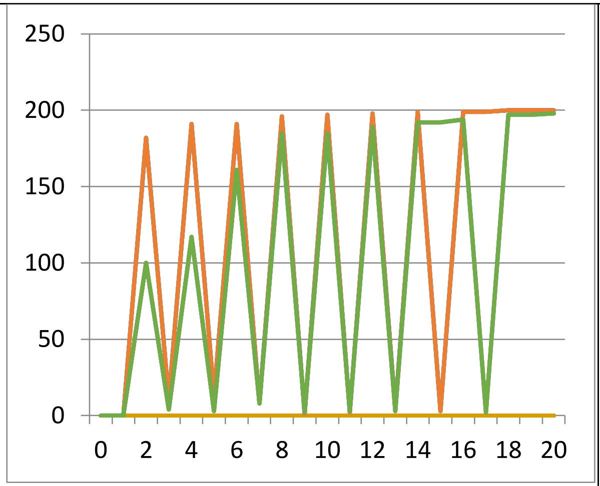
Level of rural activities initiated by user agents over time through land chief resource access rights when a new State land regulation is introduced



Level of rural activities initiated by user agents over time through land chief resource access rights when a new local community land regulation is introduced



ATTACHED FIGURE E

<table>
<tr><th colspan="4">FIGURE E: STATE NEW LAND REGULATION INTRODUCTION</th></tr>
<tr><td>INIT</td><td>INIT A (land plot = 1 ha)</td><td>INIT B (land plot = 50 ha)</td><td>INIT C (land plot = 1000 ha)</td></tr>
<tr><td colspan="4">Number of activities realized by user agents over time through resource access rights delivered by local community agents</td></tr>
<tr><td>STATE LEVEL</td>
<td>
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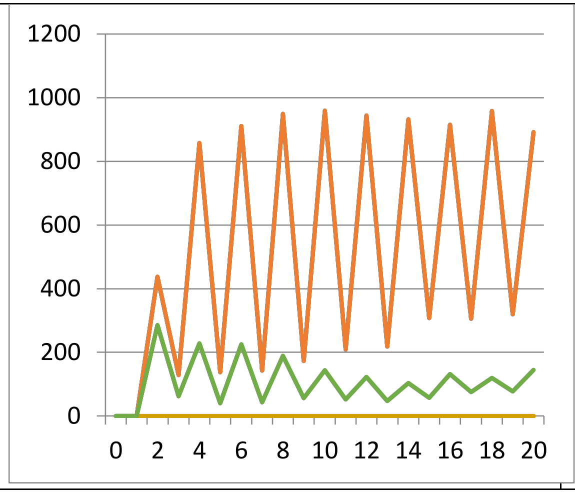
<td>
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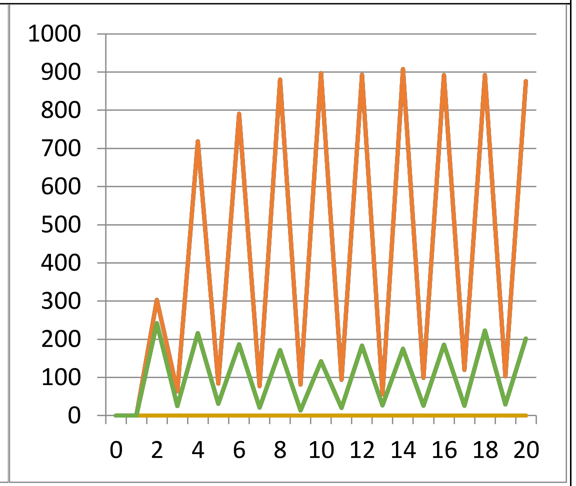
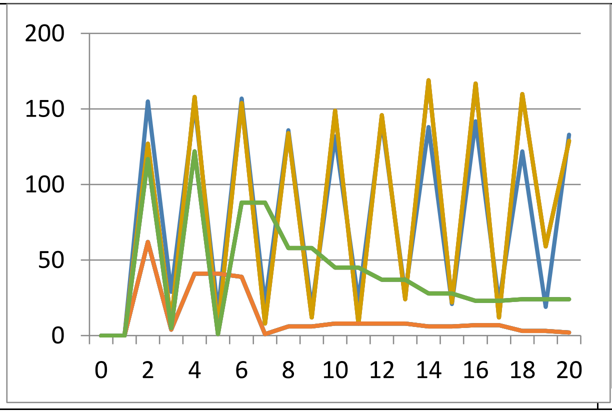
<td>
</td></tr>
<tr><td>LEGEND</td><td colspan="3">Probe color violet/blue = no new land regulation introduced // Probe color red = randomly spread introduction of the State new land regulation source //Probe color orange = contiguously localized introduction of the State new land regulation source</td></tr>
<tr><td colspan="4">Number of activities realized by user agents over time through resource access rights delivered by land chief agents</td></tr>
<tr><td>LAND CHIEF LEVEL</td>
<td>
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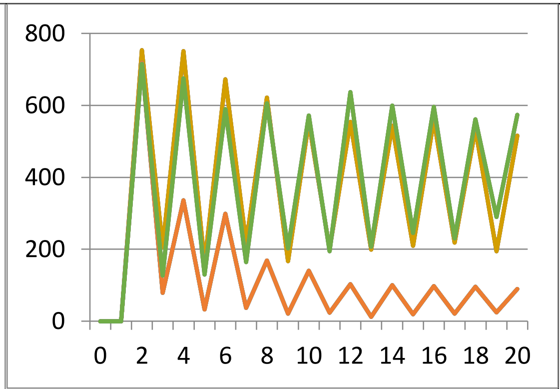
<td>
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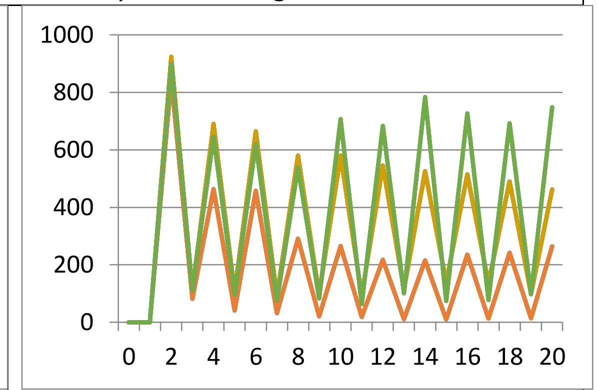
<td>
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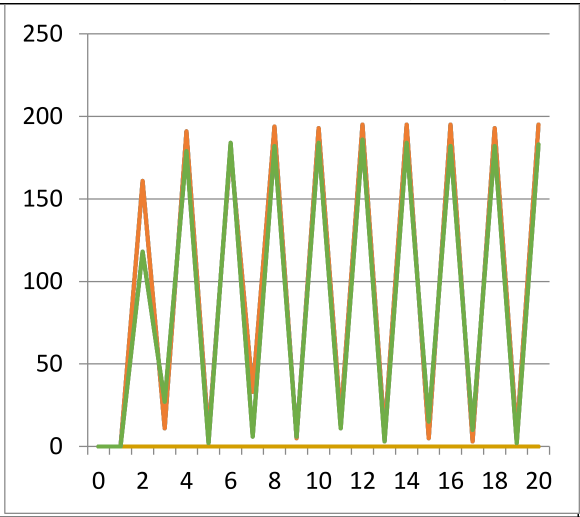
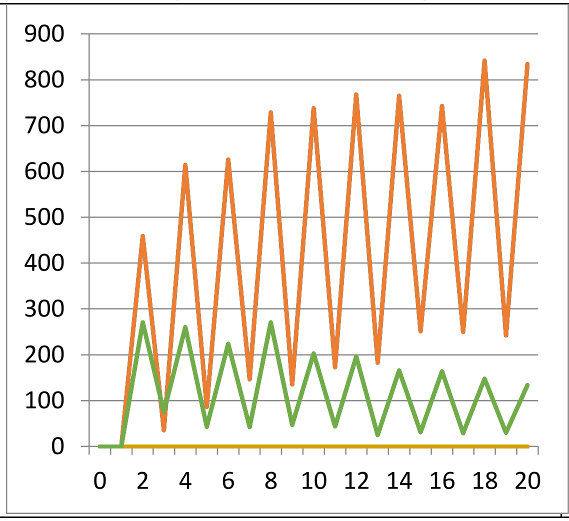
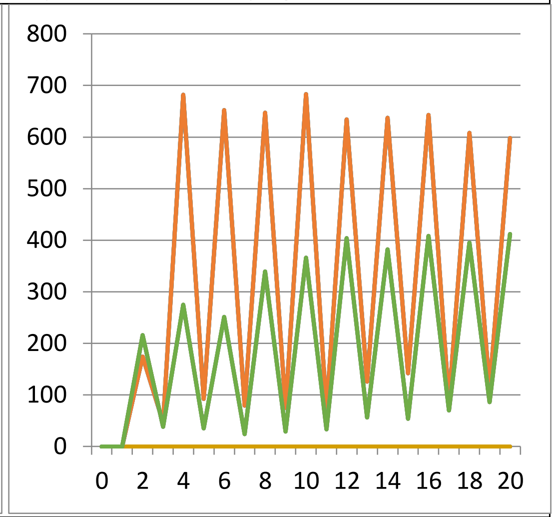
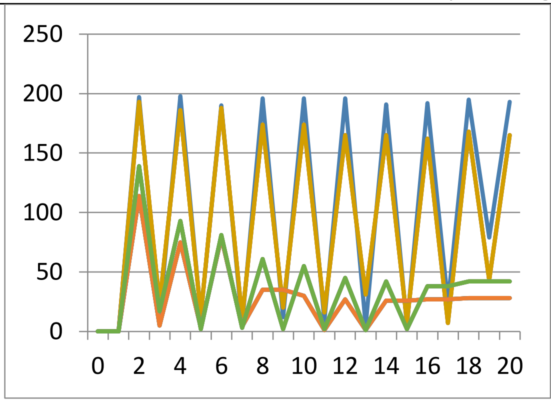
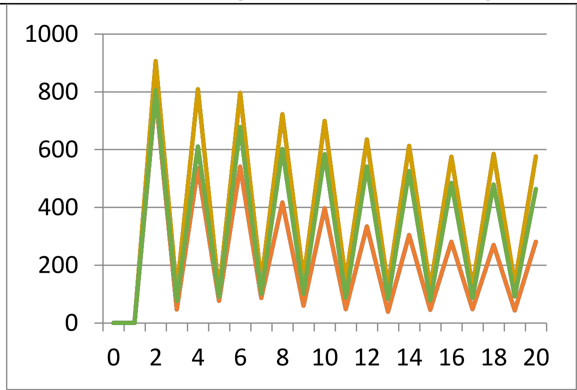
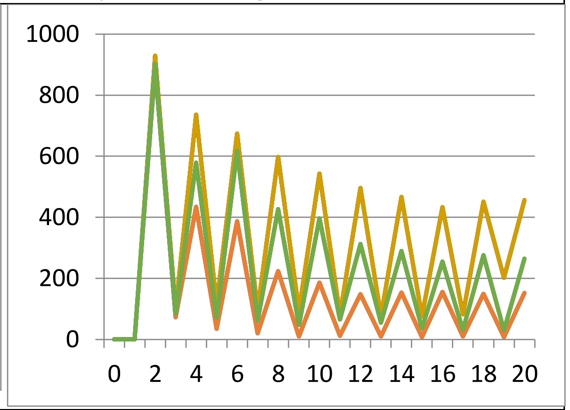
<table>
<tr><th colspan="4">LOCAL COMMUNITY NEW LAND REGULATION INTRODUCTION</th></tr>
<tr><td>INIT</td><td>INIT A (land plot = 1 ha)</td><td>INIT B (land plot = 50 ha)</td><td>INIT C (land plot = 1000 ha)</td></tr>
<tr><td colspan="4">Number of activities realized by user agents over time through resource access rights delivered by local community agents</td></tr>
<tr><td>LOCAL
COM
LEVEL</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>LEGEND</td><td colspan="3">Probe color violet/blue = no new land regulation introduced
Probe color red = randomly spread introduction of the State new land regulation source
Probe color orange = contiguously localized introduction of the State new land regulation source</td></tr>
<tr><td colspan="4">Number of activities realized by user agents over time through resource access rights delivered by land chief agents</td></tr>
<tr><td>LAND
CHIEF
LEVEL</td><td>
</td><td>
</td><td>
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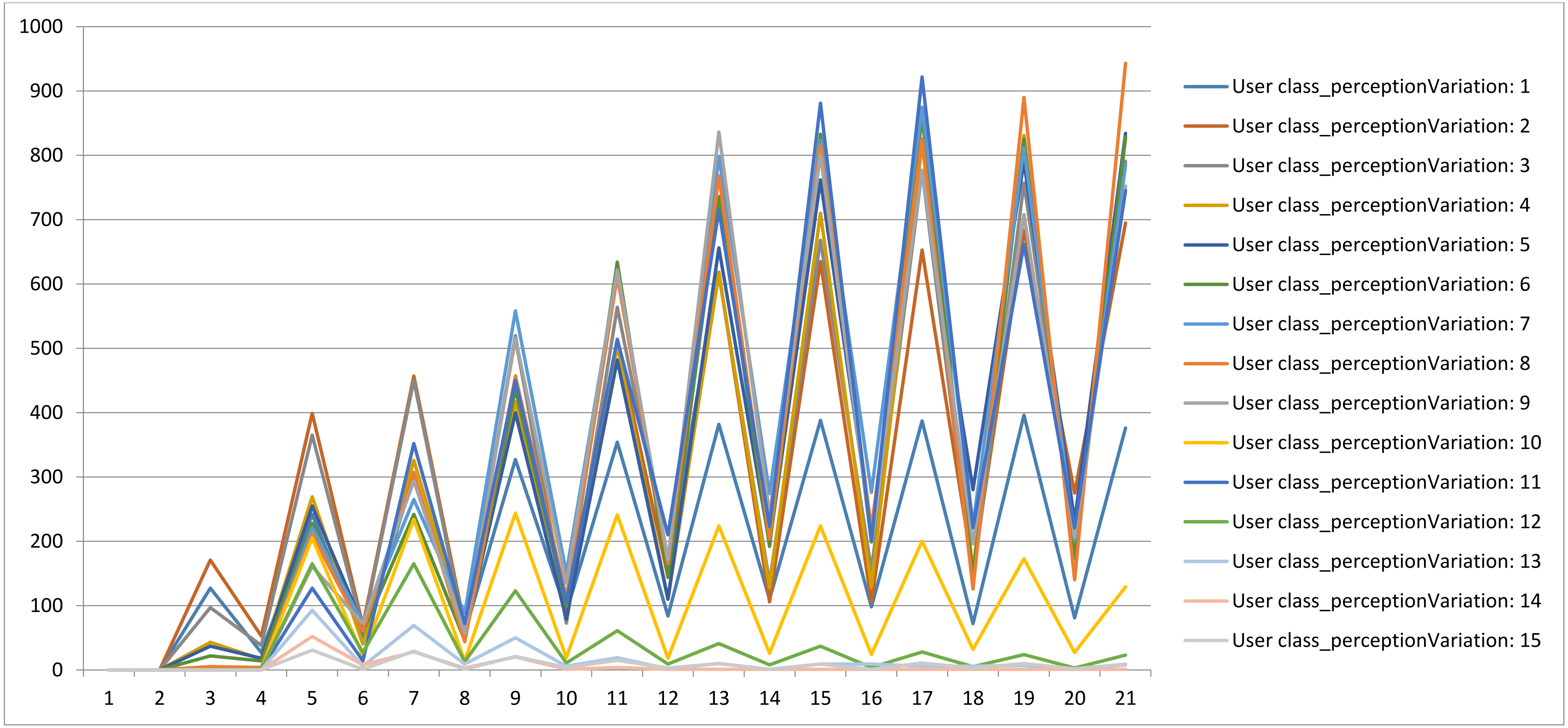
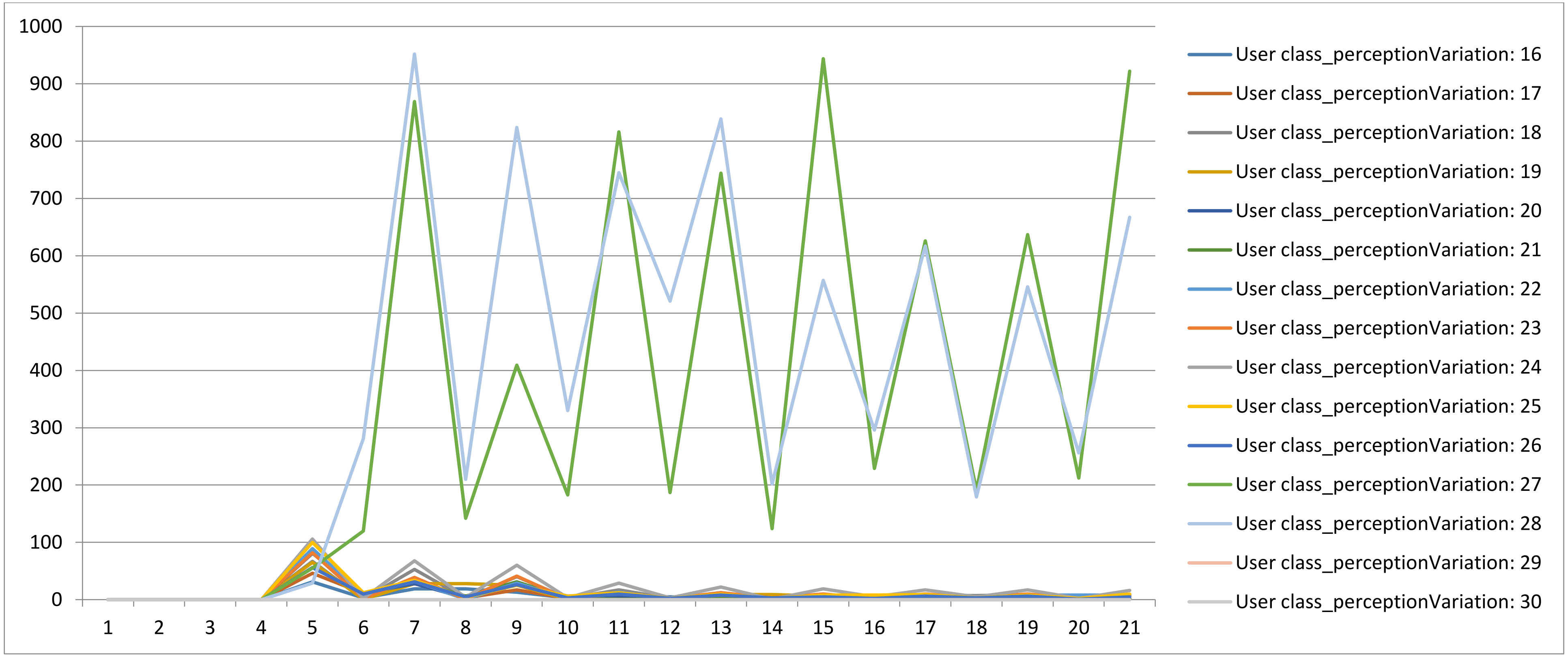
ATTACHED FIGURE G

SIMULTANEOUS RANDOMLY SPREAD INTRODUCTION OF THREE NEW LAND REGULATION SOURCES (INTENSITY VALUE: 30, NUMBER OF CONCERNED LAND PLOTS: 20)

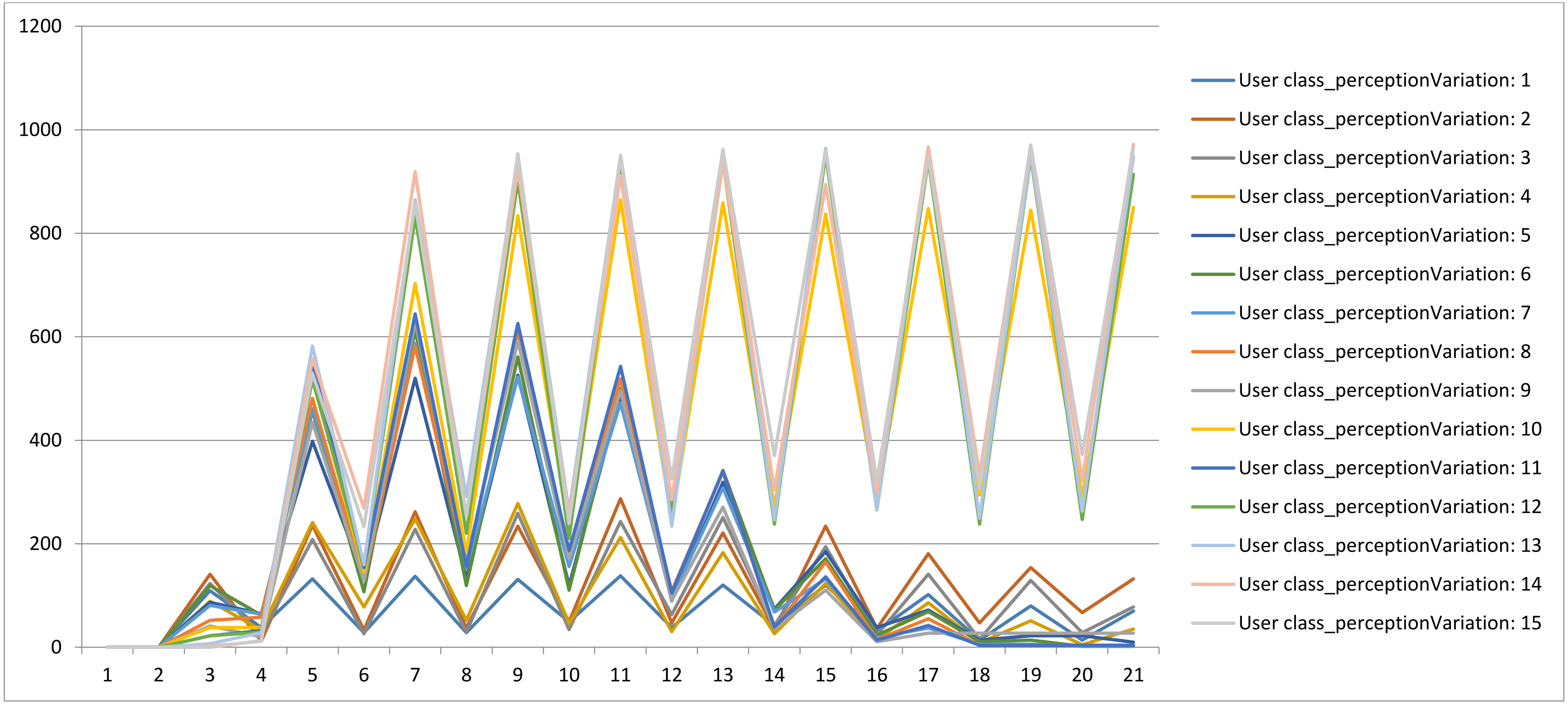
G.1 Number of activities realized by user agents through resource access rights delivered by local community agents, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



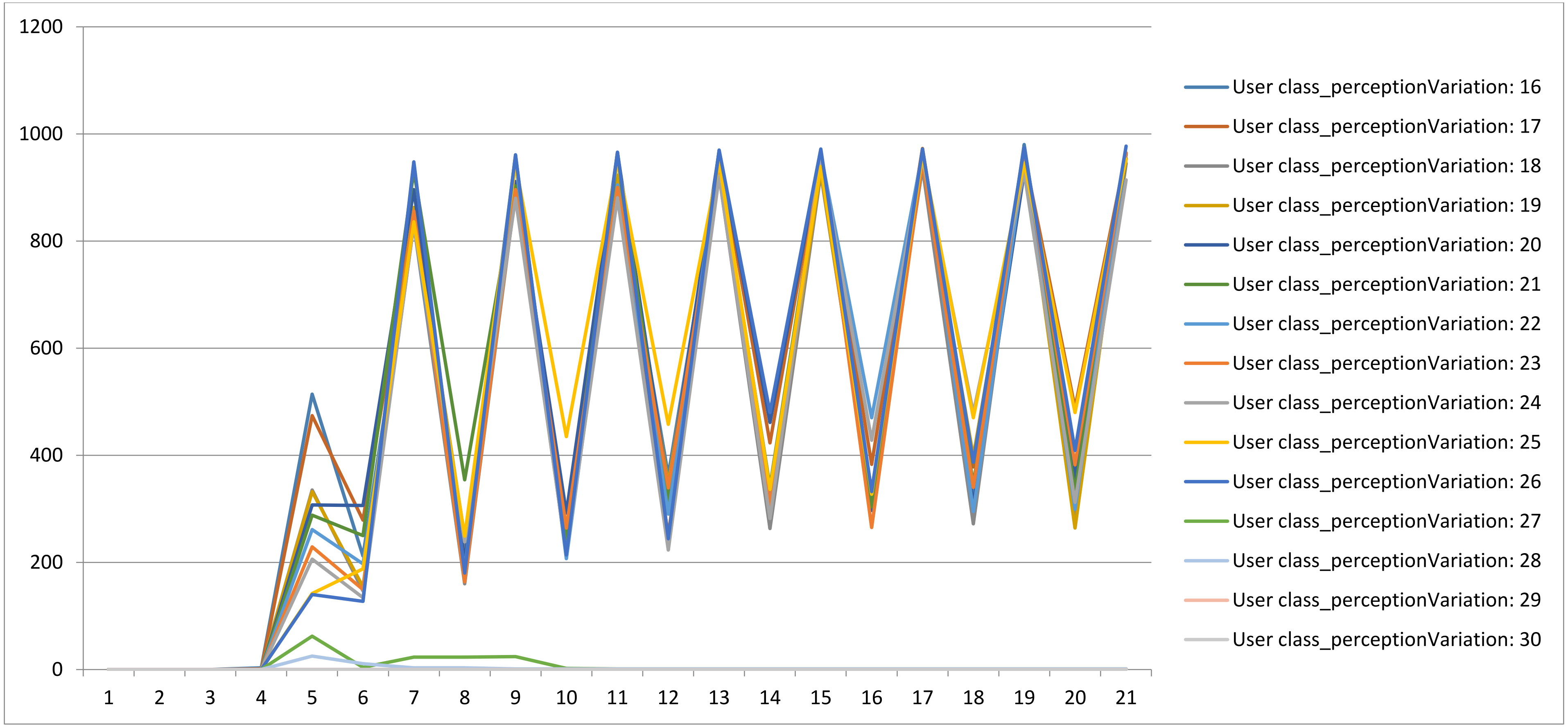
G.2 Number of activities realized by user agents through resource access rights delivered by local community agents, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



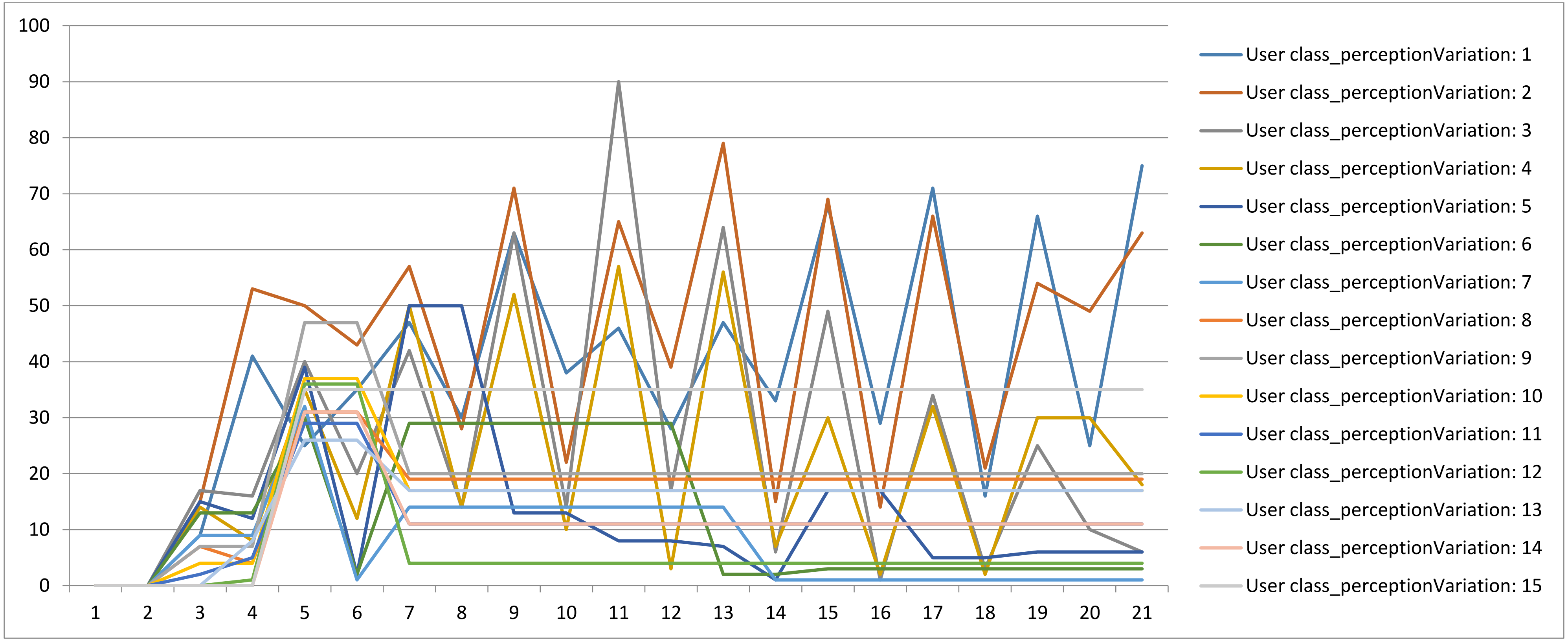
G.3 Number of activities realized by user agents through resource access rights delivered by the State agent, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



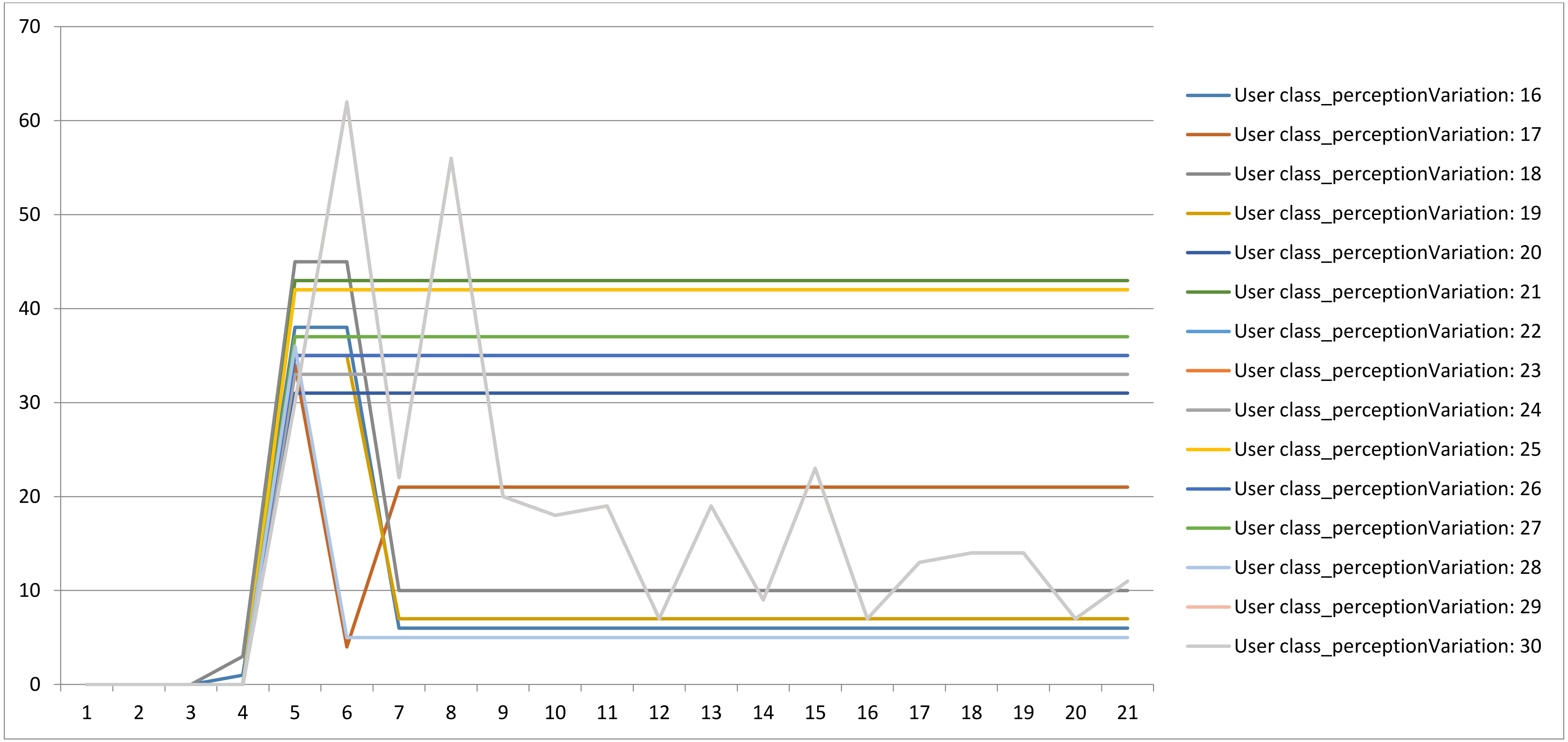
G.4 Number of activities realized by user agents through resource access rights delivered by the State agent, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



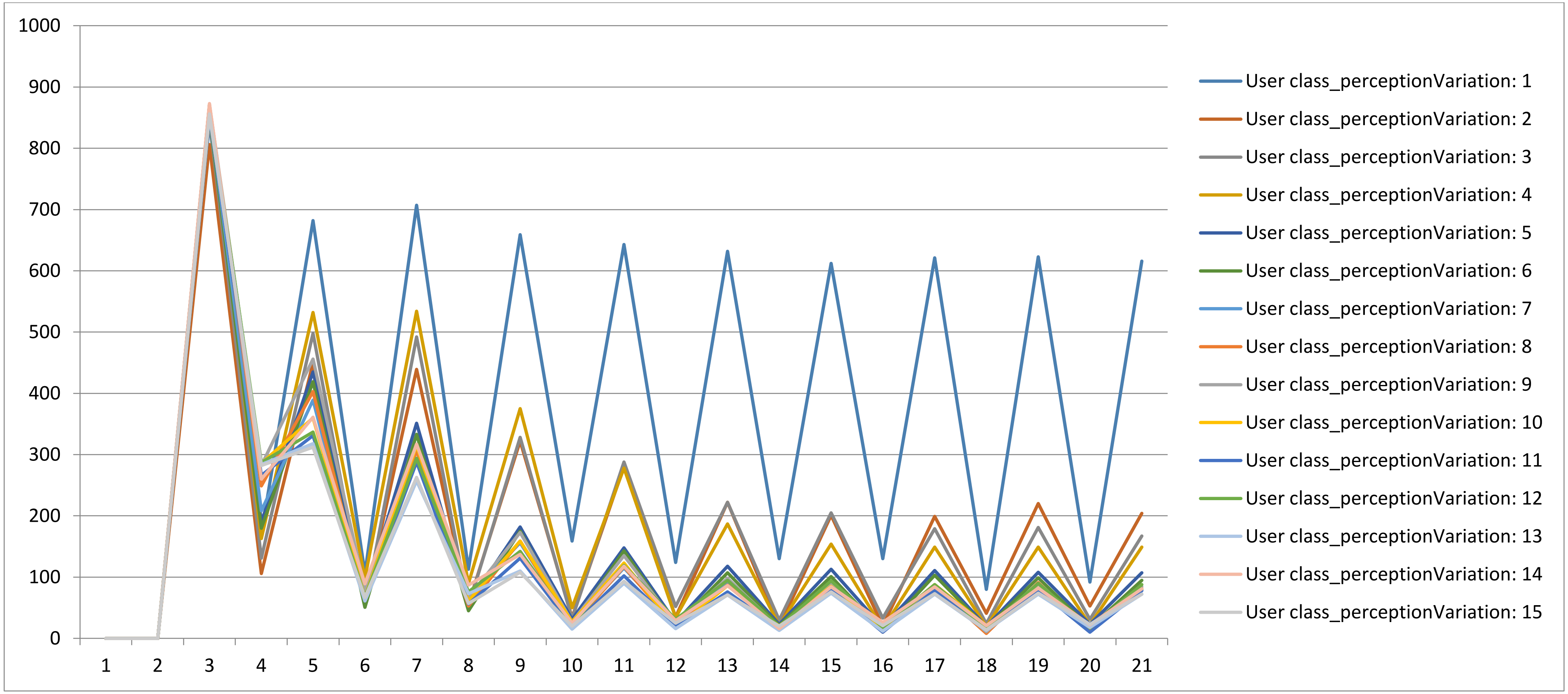
G.5 Number of activities realized by user agents through resource access rights delivered by user-regulator agents, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



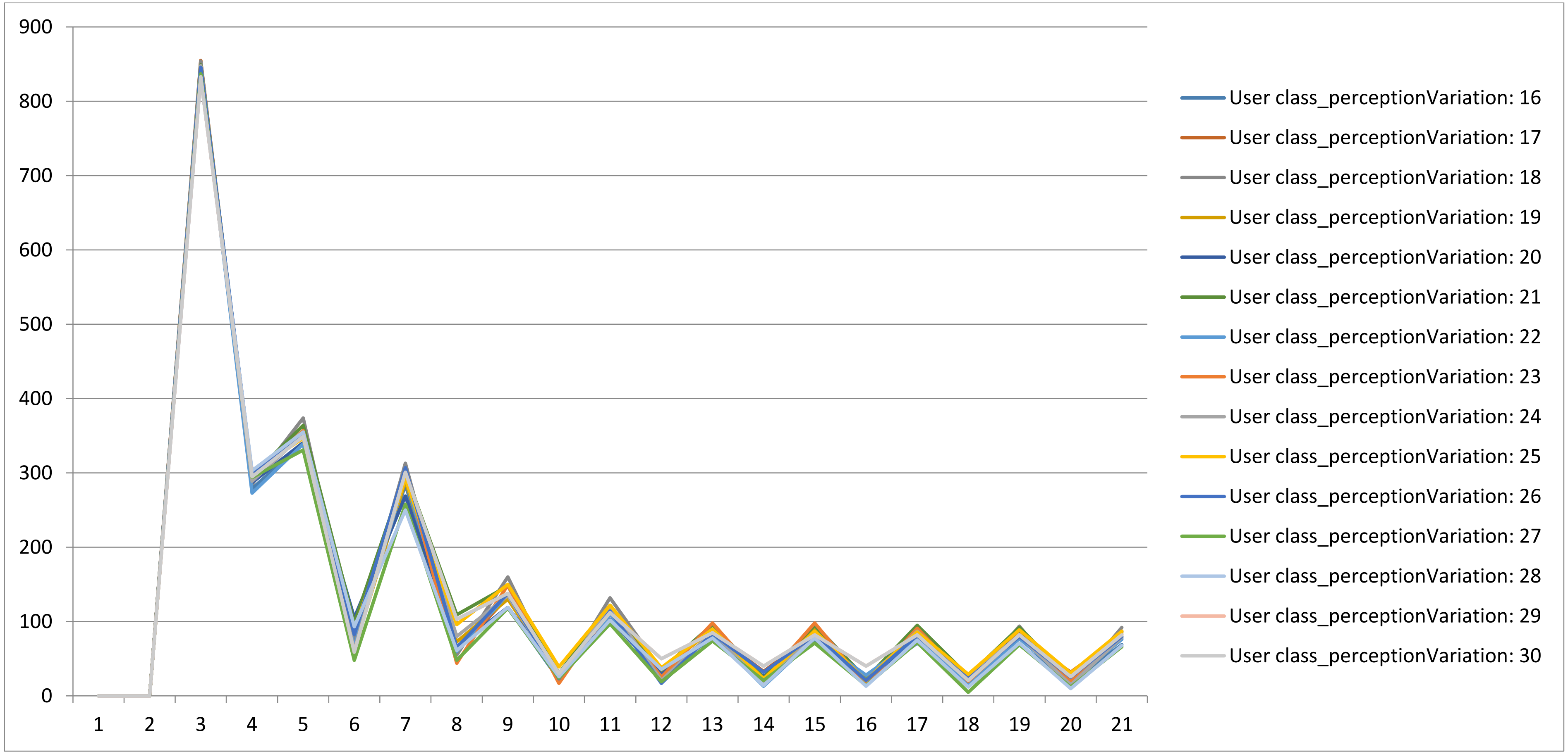
G.6 Number of activities realized by user agents through resource access rights delivered by user-regulator agents, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



G.7 Number of activities realized by user agents through resource access rights delivered by land chief agents, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



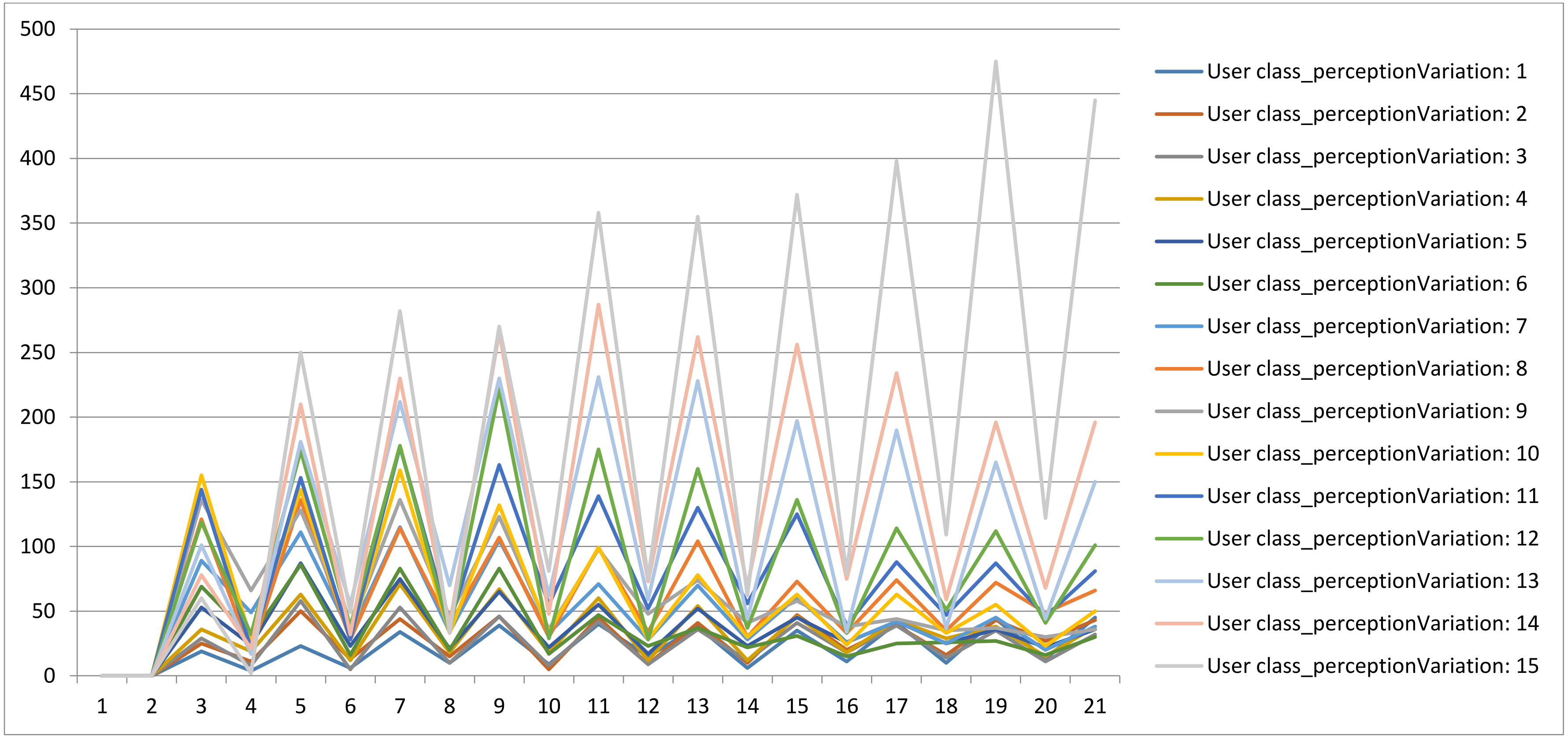
G.8 Number of activities realized by user agents through resource access rights delivered by land chief agents, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



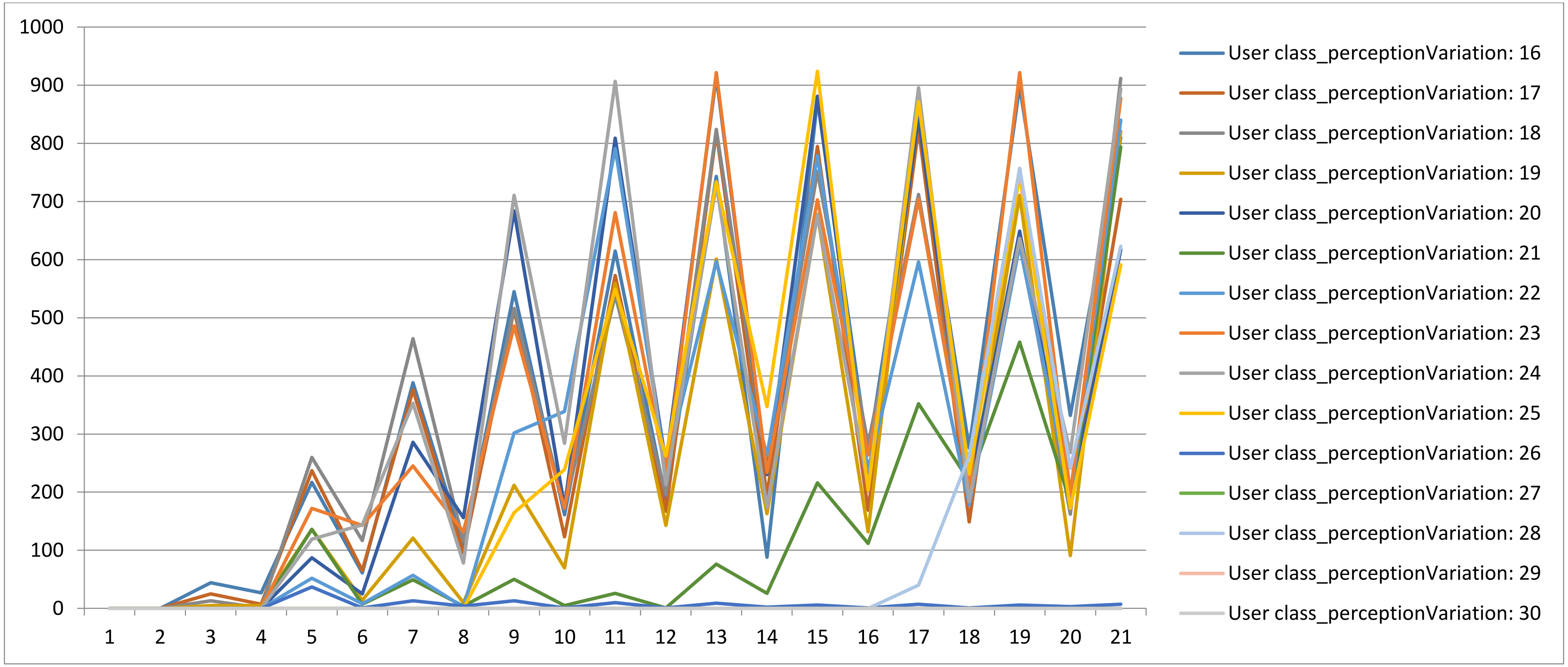
ATTACHED FIGURE H

SIMULTANEOUS CONTIGUOUSLY-LOCALIZED INTRODUCTION OF THREE NEW LAND REGULATION SOURCES (INTENSITY VALUE: 30, NUMBER OF CONCERNED LAND PLOTS: 20)

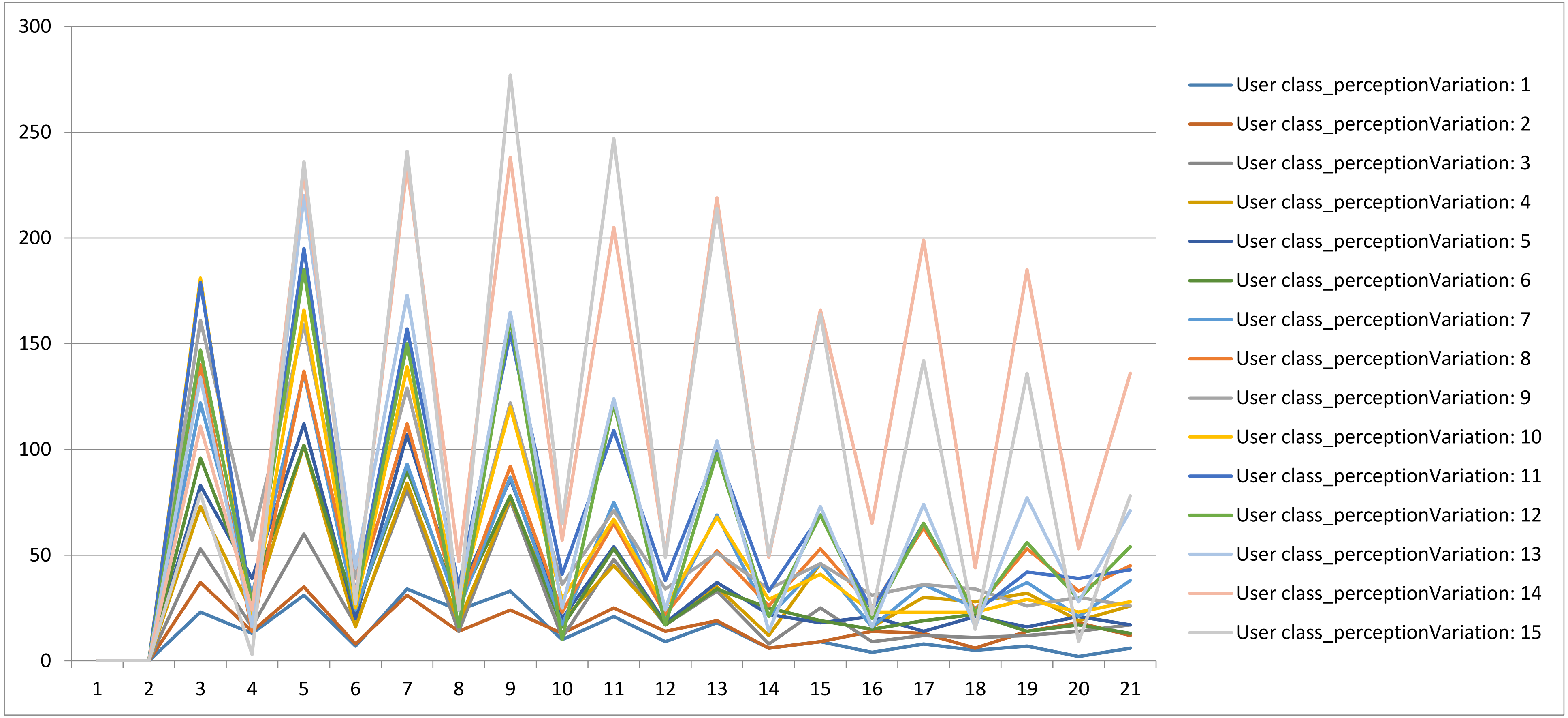
H.1 Number of activities realized by user agents through resource access rights delivered by local community agents, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



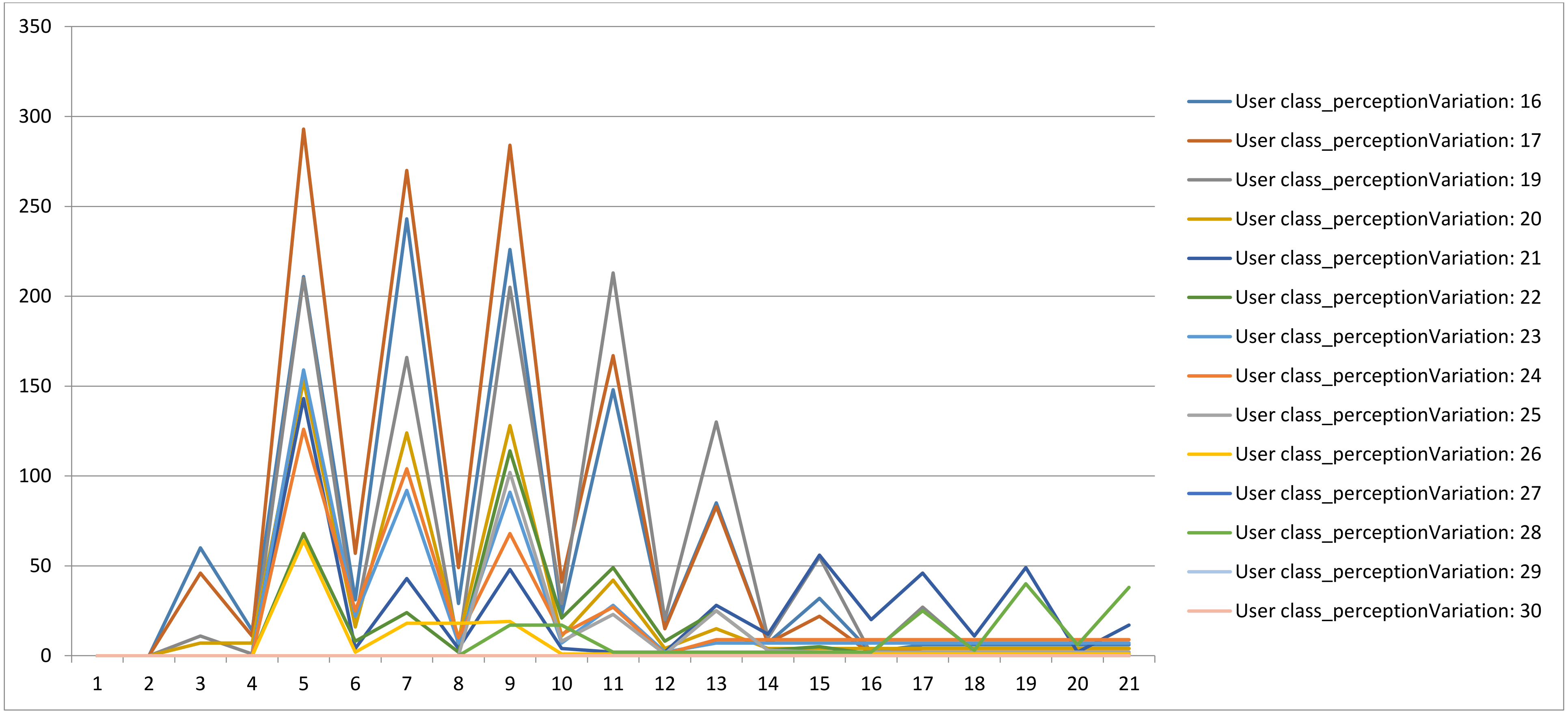
H.2 Number of activities realized by user agents through resource access rights delivered by local community agents, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



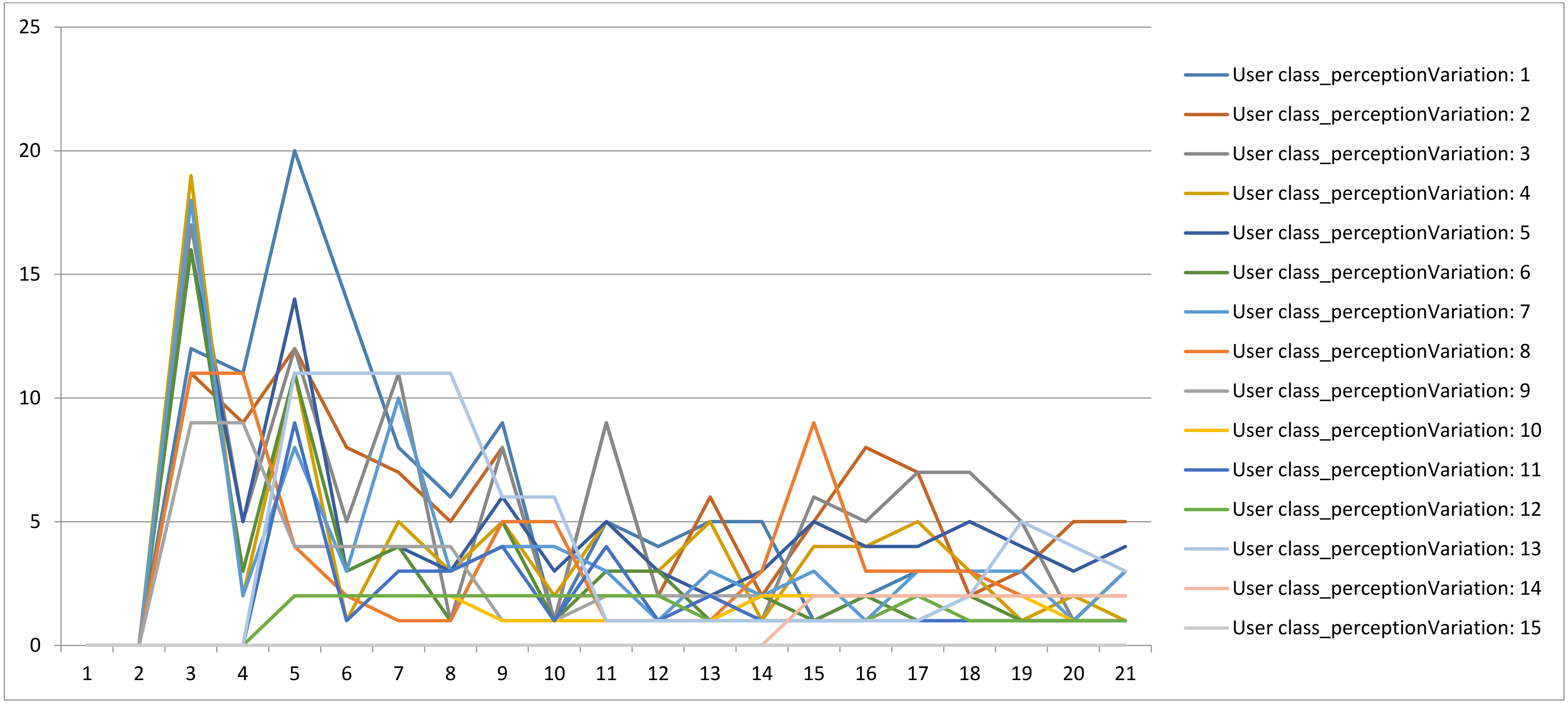
H.3 Number of activities realized by user agents through resource access rights delivered by the State agent, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



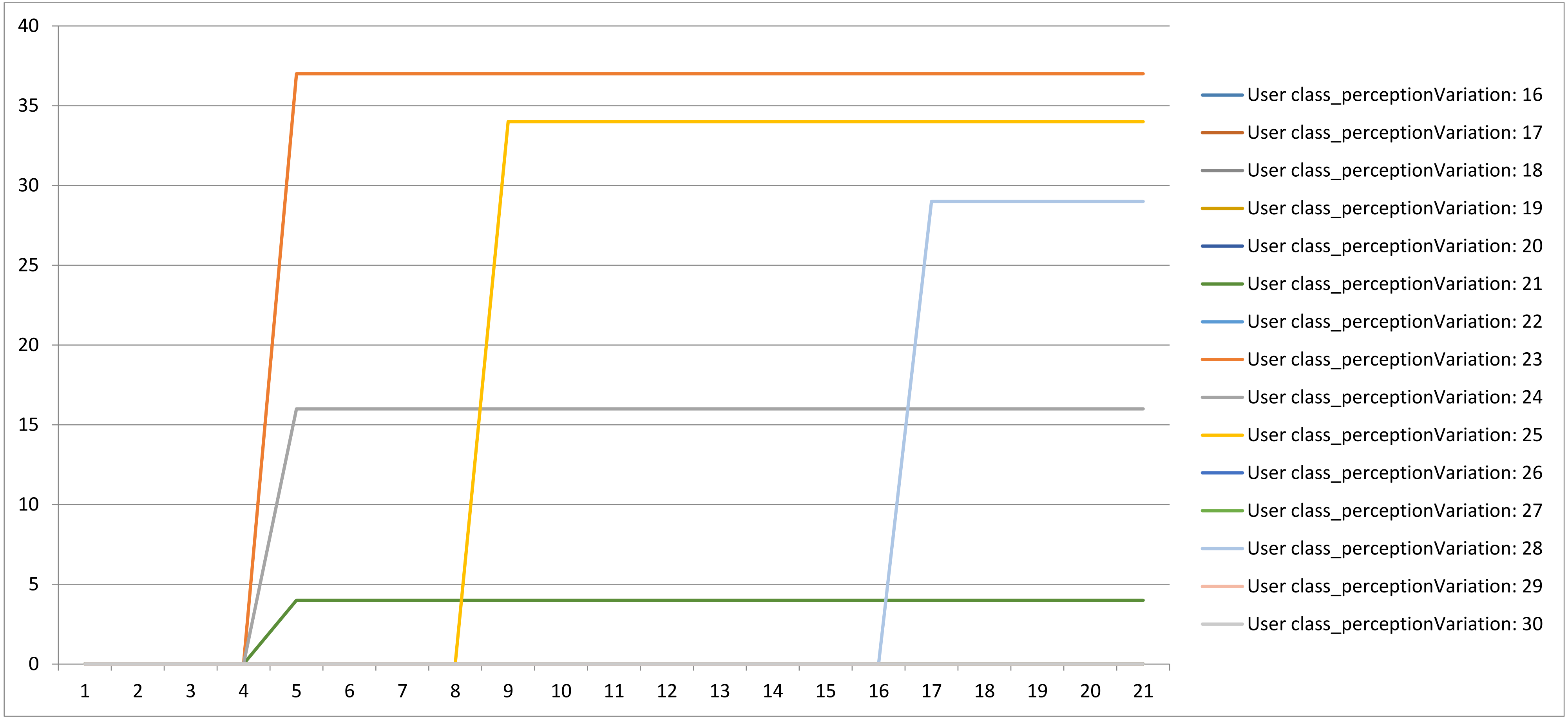
H.4 Number of activities realized by user agents through resource access rights delivered by the State agent, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



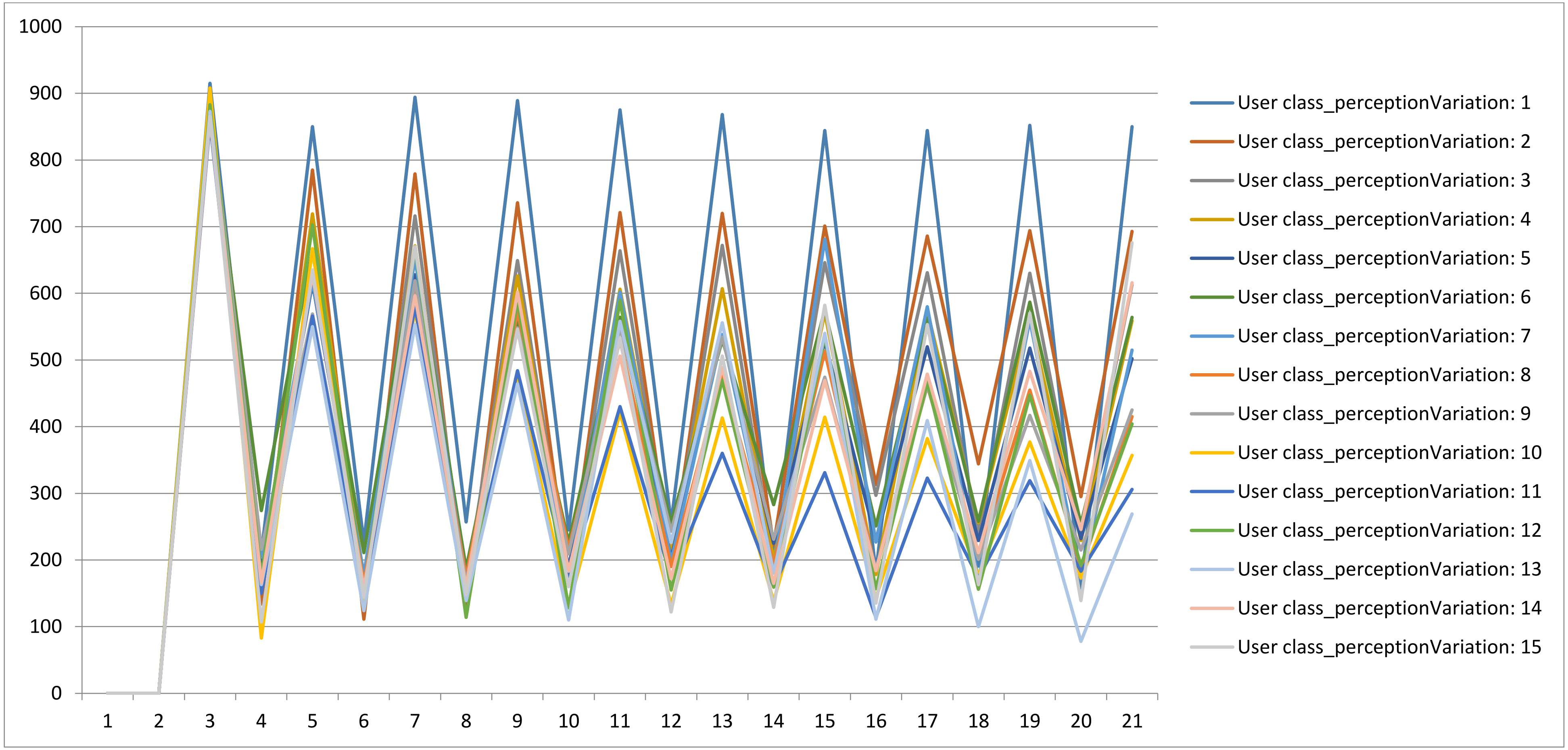
H.5 Number of activities realized by user agents through resource access rights delivered by user-regulator agents, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



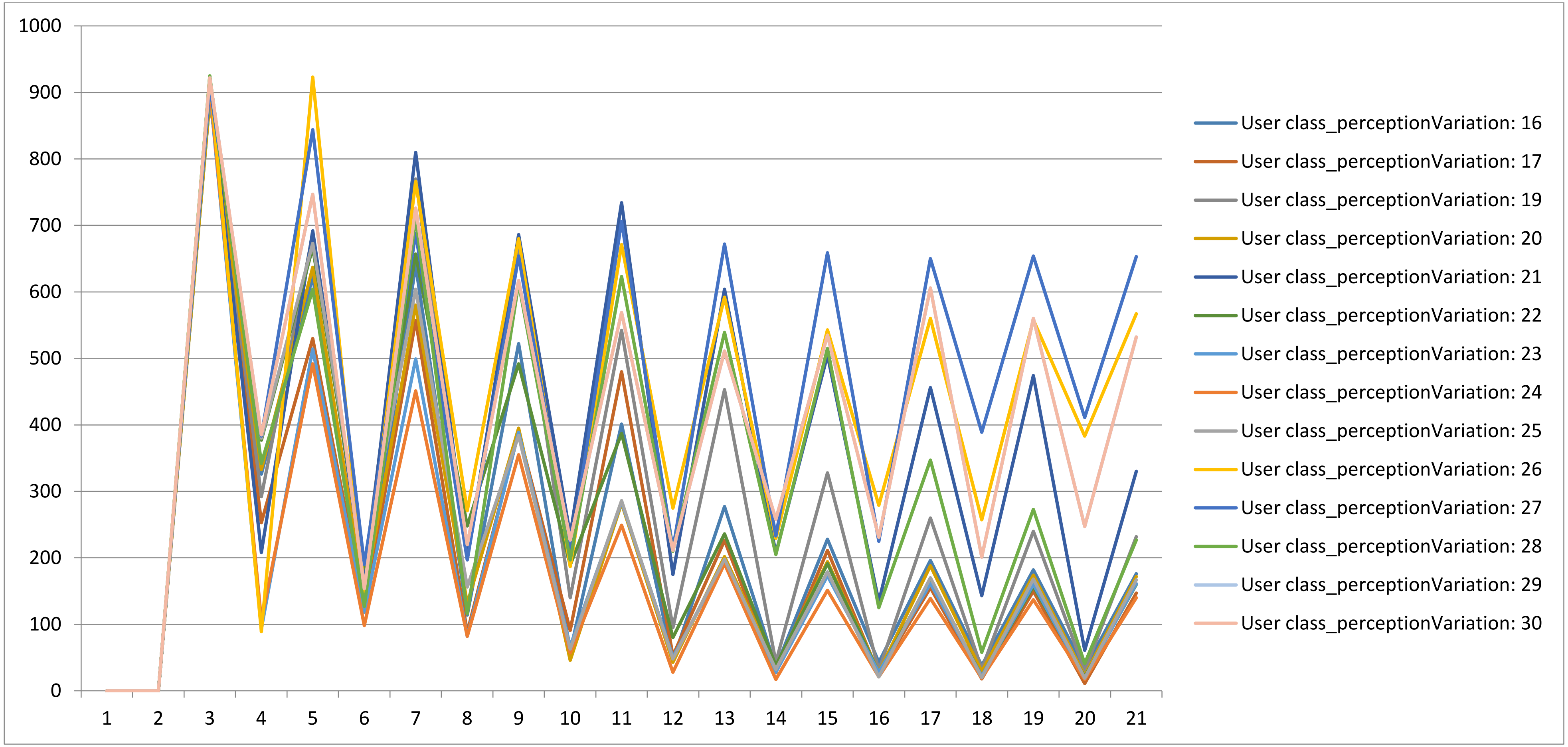
H.6 Number of activities realized by user agents through resource access rights delivered by user-regulator agents, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).



H.7 Number of activities realized by user agents through resource access rights delivered by land chief agents, according to the value of user perception of natural resources and their regulations (for a value interval of 1-15).



H.8 Number of activities realized by user agents through resource access rights delivered by land chief agents, according to the value of user perception of natural resources and their regulations (for a value interval of 16-30).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